Critical Infrastructure Protection and Resilience Literature Survey: Modeling and Simulation

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Defence Research and Development Canada
DRDC-RDDC-2014-C284
November 2014

IMPORTANT INFORMATIVE STATEMENTS

CI Interdependency Model Development in Support of Federal Government Continuity CSSP-2013-TI-1039 was supported by the Canadian Safety and Security Program which is led by Defence Research and Development Canada's Centre for Security Science, in partnership with Public Safety Canada. The project was led by Public Safety Canada in partnership with National Research Council.

Canadian Safety and Security Program is a federally-funded program to strengthen Canada's ability to anticipate, prevent/mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology with policy, operations and intelligence.

NRC·CNRC Knowledge Management

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DRDC Project # CSSP-2013-TI-1039

NRC Project # 18526

Report submitted on December 13, 2013

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1 EXECUTIVE SUMMARY

Defence R&D Canada's Centre for Security Science (CSS) is working in partnership with Public Safety Canada (PS) on a long term objective to develop an integrated national and regional Critical Infrastructure (CI) Dependency model for CI risk analysis and risk mitigation in support of the 2010 National Critical Infrastructure Strategy.[1] To frame discussions and serve as a starting point, CSS has requested NRC Knowledge Management to perform an exploratory study of existing scientific, industrial and government (domestic/international) literature on critical infrastructure protection and resilience (CIPR) and related concepts; including, but not limited to, CI interdependencies as well as modeling and simulation tools.

This report focuses on modeling and simulation tools and trends. In all, 2,151 publications, including a sub dataset of 633 publications specifically focused on interdependency modeling and simulation, were retrieved and analyzed using text mining software and a variety of visualization tools to identify trends in the literature and key players. Additionally a listing of 113 tools found in the dataset are also provided, among which 82 tools focused on interdependency modeling or simulation, 18 focused on regional or local modeling or simulation, and 13 focused on government/business continuity modeling and simulation with some repeats between groups. Government/business continuity tools are used most frequently to model and simulate CIPR in the *Energy and Utilities* and *Water* sectors. Other highlights of the datasets are provided in Table 1.

The similarities between the two data sets (CIPR modeling and simulation and CIPR interdependency modeling and simulation) are quite notable. It is possible that the subfield of CIPR interdependency modeling and simulation is still depending on tools and techniques used in general CIPR modeling because it has not yet developed enough of its own tools and techniques. Ouyang[2] argues that there is still a need for a new concept that can "integrate different approaches into a single framework and co-simulation platform to address different aspects of interdependent" critical infrastructure. This view is supported by the general lack of specific best practices or lessons learned in the literature that was reviewed, i.e. the field of modeling and simulating critical infrastructures, and in particular CI interdependencies, has not yet matured. In general, articles that did provide best practices, lessons learned, or recommendations were either presented at a higher level of managing risks or disaster response or were more specific to the tool being presented and not easily generalized to modeling and simulation of CI interdependencies.

Alternatively it may be that the tools and techniques that are used in general CIPR modeling are sufficiently applicable to interdependency modeling. More time and testing of these techniques would be required to determine the true cause of the overlap. Revisiting the numerous projects and programs that are presented would allow one to keep a finger on the pulse of developments in this area.

A number of agreed upon challenges in the field of CI interdependency modeling and simulation include insufficient access to data; incorporating less commonly studied CI in models and simulations to improve disaster mitigation and recovery; integrating a variety of tools and techniques into an open framework to compensate for varying levels of error, uncertainty and conflicting results; validating new models in ever changing environments and finally, dealing with the general lack of theories and generic results that are easily generalized to actual infrastructure.

A brief overview of findings pursuant to the key questions of the project is included in Table 1.

Table 1. Summary of Findings: Key Questions

Topic	CIPR M&S Tools in General	CIPR Interdependency M&S Tools
Top Author Affiliations	The United States, Italy and Canada are the leading countries in CIPR modeling and simulation, with roughly an equal distribution between governmental and academic affiliations. University of British Columbia, York University and Western University top the Canadian affiliations list.	Polytechnic University of Milan (Italy), Huazhong University of Science and Technology (China), University Campus Bio-Medico of Rome, Rice University (U.S.), the Italian National Research Council (CNR), TNO Defense (Netherlands) and Gjøvik University College in Norway. University of British Columbia, York University and Western University remain the top the Canadian affiliations
Top Critical Infrastructures	Energy and Utilities, Information and Communication Technology, Safety, Transportation and Cyber.[a]	Energy and Utilities, ICT, Transportation, Safety and Water.
Top Threats	Terrorism, Disasters, Earthquakes, CBRNE, Natural disasters	Disasters, Terrorism, Earthquakes, Natural disasters and Floods
Common M&S Techniques	Dynamic Modeling and Simulation (M&S), Estimation, Statistical/Numerical techniques, Classification/Pattern Identification, and Geographic Information Systems (GIS) and Graph Theory/Models	Dynamic M&S, Estimation, GIS, Input-Output Modeling and Classification/Pattern Identification. Regional tools use Dynamic M&S, DIIM, GIS and Forecasting. Regional tools are used for M&S Safety critical infrastructures as much as Energy and Utilities.
Emerging M&S Techniques	Behavioral Analysis, Monte Carlo techniques, Clustering and Petri Nets	Bayesian techniques, Hierarchical Methods, Clustering, Graph Theory/Model, Monte Carlo, Tree Analysis and Dynamic Inoperability Input-Output Model (DIIM)
New or Pre-Emerging Techniques	Tree Analysis, Bayesian, Input-Output Modeling, Fuzzy techniques and Hierarchical Methods	Inconclusive
Outliers	Game Theory for terrorist threats	Input-Output Modeling used equally as frequently for Finance as for Energy and Utilities; Hierarchical methods in ICT

The authors would like to thank Tamara Keating at the National Research Council of Canada's Knowledge Management Department for her helpful review and comments on this report.

[a] *Cyber* was considered separately from *ICT* because of the volume of publications that focused specifically on cyber issues and the fact that less than half co-occurred with *ICT* thus arguably warranting its own examination.

2 BACKGROUND

2.1 Context

In 2009, the Canadian federal government, provinces and territories agreed on a National Strategy and Action Plan for Critical Infrastructure. The purpose of this initiative is to strengthen the resilience of Canadian Critical Infrastructure (CI) by building partnerships, implementing hazards risk management approaches, and advancing the timely sharing and protection of information among partners. The strategy recognized that critical infrastructures are at risk from natural, intentional and accidental hazards and that the risk could be exacerbated by the complex system of interdependencies among critical infrastructure, which can lead to cascading effects across borders and sectors. The Action Plan includes the establishment of sector networks and a cross-sector forum as the basis for collaborative work and information sharing. The Centre for Security Science (CSS) is working in partnership with Public Safety Canada (PS) on initiatives to address some of the objectives identified within the strategy and its action plan in order to increase Canadian infrastructure resiliency, develop strong communities and implement an all-hazards risk management approach. The continuity of national governance to maintain public health, safety, security, economic well-being and the confidence during or after any disaster or emergency is one of the initiatives. The development of national and regional interdependency modeling tools and methodologies to understand CI interdependencies and the cascading effect of events is another important initiative.

2.2 Key Issues

To frame discussions and serve as a starting point in the development of a national and regional CI interdependency modelling tool, CSS has requested an exploratory study of existing scientific, industrial and government (domestic/international) literature on critical infrastructure protection and resilience (CIPR) and related concepts; including, but not limited to, CI interdependencies as well as modeling and simulation. This study will examine the existing body of knowledge and attempt to structure the current state of knowledge of CIPR modeling and simulation and CIPR interdependency modeling and simulation. It is anticipated that the results of this work will yield a more in depth and enhanced understanding of the concepts, activities and tools associated with CIPR in terms of physical and cyber security systems from both civilian and military perspectives. Additionally, it will help CSS develop advanced capabilities and expertise in the area, as well as highlight gaps, lessons learned and opportunities for next steps in the pursuit of an integrated CIPR strategy.

2.3 Key Questions

1. What is the state of CIPR modeling, simulation and analysis (both in terms of risk modeling for CI and modeling protection and resilience)? Provide an overview of the available tools (by types, not specific names of tools).
2. Identify and provide an overview of tools that model, simulate and analyze CIPR interdependency as well as regional (in Canada and the US) CIPR risks and capabilities. Identify, when possible, the applicability and challenges for these tools.
3. Are there any tools that focus on CI interdependency modeling in support of government continuity?
4. What are the key observations/lessons learned in CI modeling particularly interdependency modeling?

3 INTRODUCTION

To address the key questions, data was gathered from four bibliographic databases. The complete list of sources and the search strategy are described in detail in the *Methodology* section (7) of this report. The dataset was divided into two subsets. The first, referred to hereafter as the *master set*, includes all records found in the search with a total of 2151 records published between 2003 and 2013. The second, referred to hereafter as the *interdependency set*, was a sub dataset created by copying all records that had the term interdependency, independency, dependent, dependency, regional, or local (and any other synonyms in the dataset) and totalled 633 records. Analyses on the master set include records from the interdependency set.

Figure 1 depicts the publication rate for both datasets.[b] While both lines follow a similar pattern, and both sets show a slight drop in 2012, we notice a much steeper climb in the master set since 2008 versus a flattening of the interdependency set between 2008 and 2011. This is somewhat surprising since, as Ouyang states, "modeling and simulation of interdependent CISs become a critical field of contemporary research and study".[2]

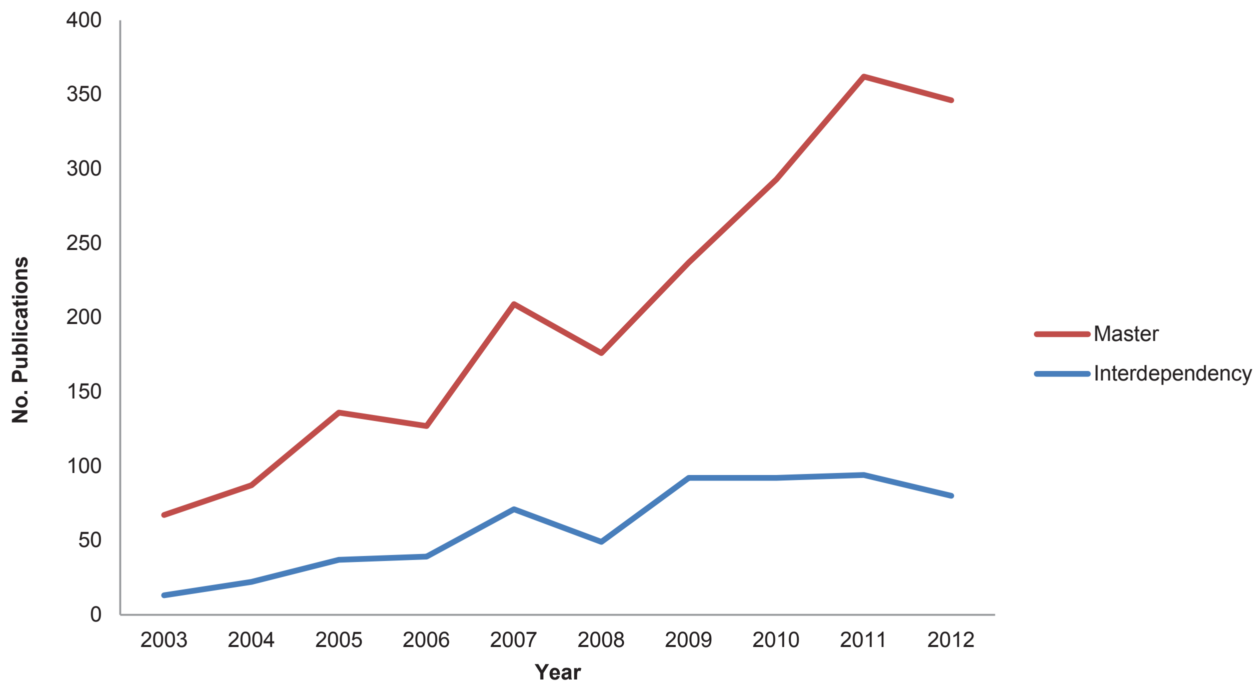

Figure 1. Master and Interdependency Data Sets, Number of Publications, 2003-2012

The data from the two sets were loaded into VantagePoint,[c] a text mining tool, where terms were cleaned and various subject groupings were created to enable analysis. The key data points or fields used for most analyses were Subjects, Publication Year and Affiliations (sponsoring organizations or institutions affiliated with the authors). The subject field is an amalgamation of author-supplied

[b] Most annual data in the project is report for 2012 as the data for 2013 did not represent a complete year at the time of data collection (October-November). If/when data is included for 2013 it is based on percentage of records in each year.
[c] VantagePoint is produced by U.S. company Search Technology, http://www.thevantagepoint.com/

keywords, controlled subject terms, and words or phrases extracted from the title and abstract fields. These subject terms were cleaned to merge singular and plural forms, to group words with very similar meaning, and to normalize vocabularies as much as possible. Two levels of subject groups were made:

Subject Groups: subject terms were organized into 122 groups based on key topics in the CIPR field as identified by literature reviews, relevant websites, and conversations with the client. The 122 subject groups cover 99% of the entire dataset.

Thematic Groups: 64 of the 122 subject groups were further categorized into four thematic "groups of groups" to enable the comparison of groups with similar themes and the detection of topics with increasing levels of research in the last five years. The four thematic groups are: *Modeling and Simulation Techniques, Critical Infrastructure, Threats,* and *Government Levels.* Table 12 in Section 7.2.1 of this report depicts the thematic classification scheme for subject groups with scope notes for each category.

Following the presentation of key players in the two sets, we present analyses of the subject groups with a particular focus on the *Modeling and Simulation* group in which we examine major and emerging trends and the co-occurrence of specific techniques with the various *Critical Infrastructure* and *Threats*.

For further study of CIPR modeling and simulation, the reader is advised to consult the following key documents in addition to those provided in the reference section.

Yusta JM, Correa GJ, Lacal-Arantegui R, Methodologies and applications for critical infrastructure protection: State-of-the-art. *Energy Policy 2011*; 39:6100-6119.

Pederson P, Dudenhoeffer D, Hartley S, Permann M. Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research. 2006: Idaho National Laboratory. http://www.inl.gov/technicalpublications/Documents/3489532.pdf (Accessed in December 3, 2013.)

4 FINDINGS

4.1 Overview of Available Tools

4.1.1 Tools in general

Yusta, Correa and Lacal-Arantegui[3] present a survey of 55 articles, reports and standards between 1999-2010 that propose different methodologies, applications and software tools for critical infrastructure protection. They identified five different modeling techniques that use either a simulation paradigm or decision-making procedure including: multi-agent systems, system dynamics, rating matrices, relation databases and network theory. They also identified seven supplementary computational methods and techniques including continuous time-step simulation, discrete time-step simulation, Monte Carlo simulation, decision trees, geographic information systems (GIS), risk management techniques or real time record. Many of these modeling techniques and supplementary techniques are found in our dataset. The authors further identify the critical infrastructures that are being modeled, the maturity and availability of the applications or platforms and their risk management stages (identification, risk assessment, prioritization of actions, implementation programs and effectiveness measurement). An in depth explanation of some of the software tools is provided as an appendix to the article.

Yusta, Correa and Lacal-Arantegui identified a number of trends through their survey. First, the authors noticed a trend to study and analyze infrastructure from construction on to the current state in which threats are evaluated and risk management frameworks are used to assess vulnerabilities. A second trend is a focus on understanding, through simulation, the dynamic behavior of critical infrastructure to identify vulnerabilities.

Pederson, Dudenhoeffer, Hartley, and Permann[4] of Idaho National Laboratory argue that "the modeling and analysis of interdependencies between critical infrastructure elements is a relatively new and very important field of study" and conduct a survey of U.S. and international critical infrastructure interdependency modeling tools to provide guidance for directing R&D to address gaps in the field. The survey presents 30 tools, the CI sector is the tool is used in, the simulation type (input-output or agent based as well as continuous or discrete), the system model (integrated or coupled), hardware/software requirements, users and maturity level. In addition to a table listing each tool and its various features, a 1-2 page overview of each tool is also provided.

4.1.2 Interdependency and Regional Tools

This study identified 113 specific tools related to interdependency or regional modelling (82 focused on interdependency, 18 focused on regional or local, 13 focused on government/business continuity modeling and simulation, with some repeats between groups). Eight articles mentioned CIPR exercises. Additional analyses were performed on the list of tools in section 4.4.2 (e.g. co-occurrence with the modeling and simulation techniques as well as critical infrastructure found in the dataset). Additionally, wherever possible, additional tools from the master set are mentioned in analyses throughout the report.

4.2 Key Players

4.2.1 Top Affiliations - Master Set

A breakdown of the top 10 publishing countries in the master set is presented in Figure 2. Unsurprisingly, of the majority of publications produced by the top 10, 55% originate in the United States (728/1313)[d]. The U.S. is followed by Italy (164 publications) with Canada (84) in third place. One potential explanation for the predominance of Italy is that the top Italian affiliation (ISPRA) is part of the European Commission's Joint Research Centre and conducts EU level research. Similarly, the second top Italian affiliation (ENEA) also works on Trans-European projects, program and initiatives, including the EU's Seventh Framework Programme for Research (FP7). Thus both these institutes, which together have 52 publications, are actually representing a pan-European effort.

[d] 1313 is the total number of unique publications produced by the top 10 affiliations. Numerous publications are affiliated with more than one country hence the addition of each country's number of publications equals 1441.

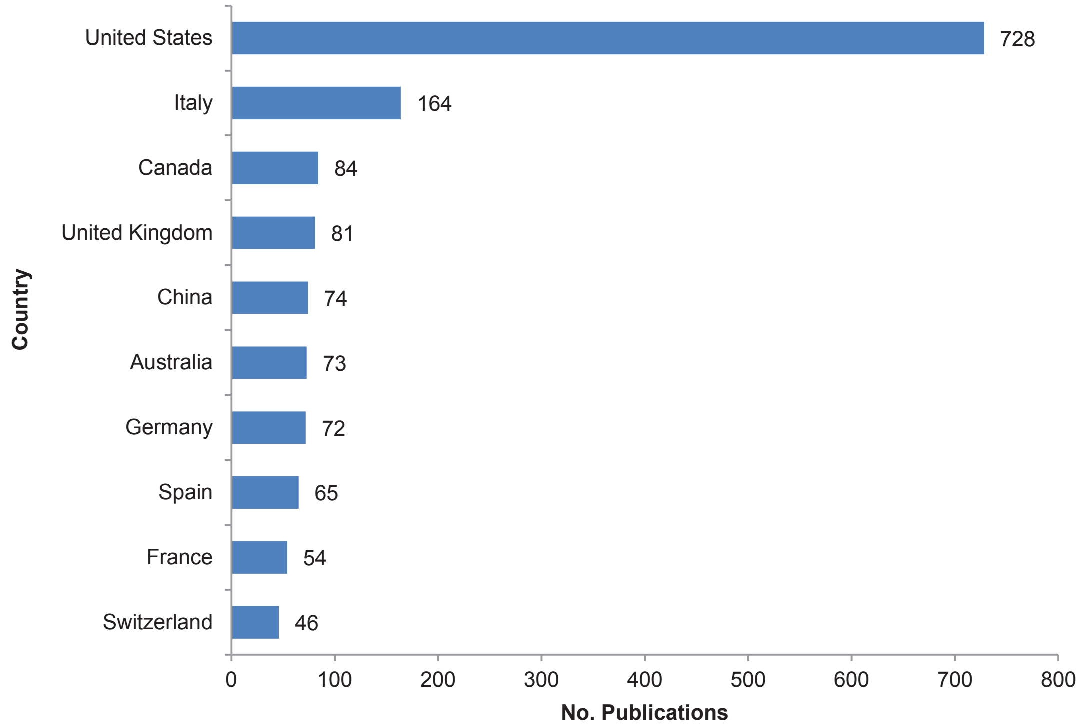

Figure 2. Master Set, Top 10 Countries

Figure 3 lists the top affiliations (≥ 20 publications) for the master set and reflects the dominance of American and Italian players. This list has 9 governmental affiliations and 7 academic institutions. A selection of the key affiliations will be examined in more detail below.

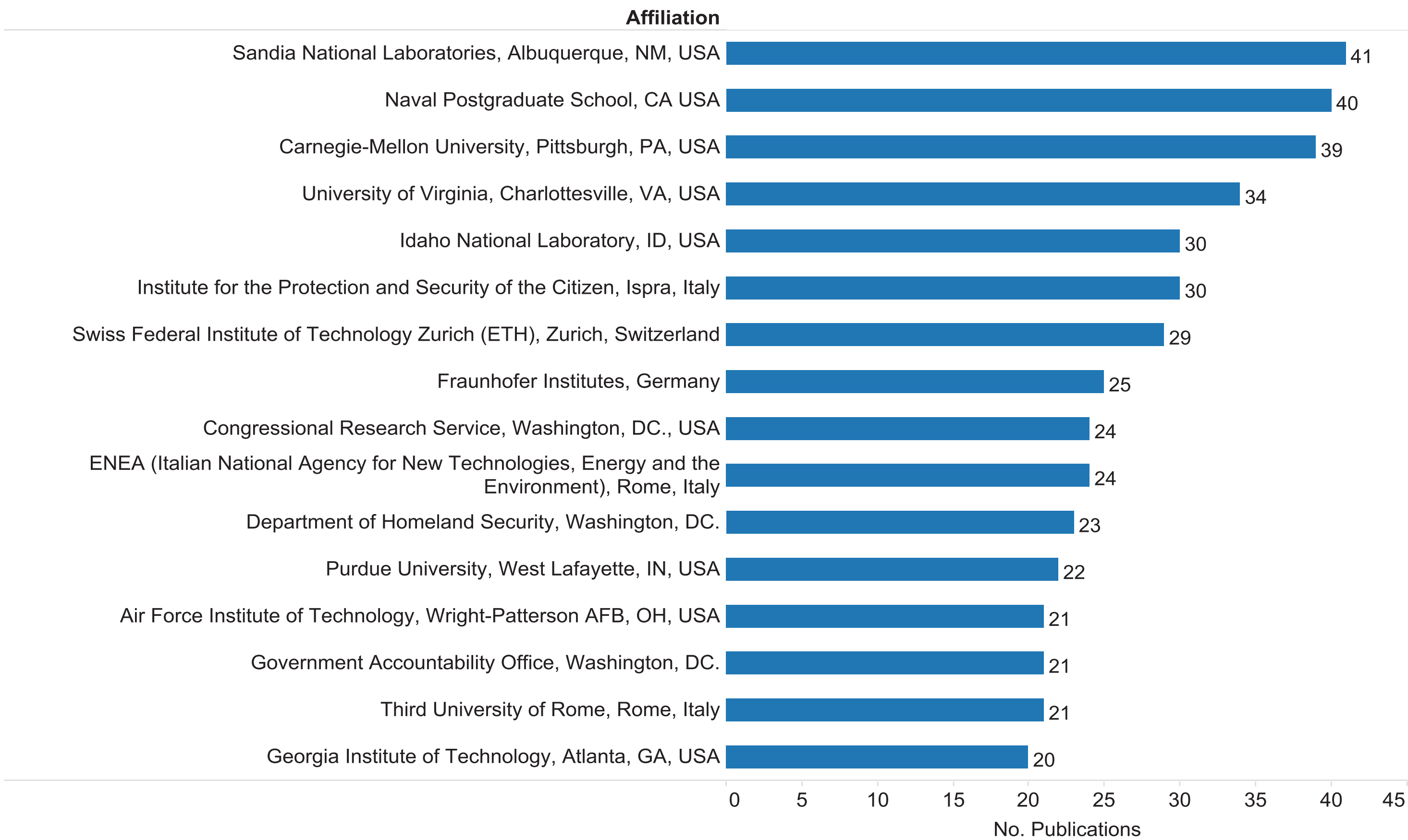

Figure 3. Top Affiliations in Master Dataset, ≥ 20 Publications, 2003-2013

Among the top U.S. governmental affiliations are Sandia National Laboratories (41 publications), Idaho National Labs (30) and the Department of Homeland Security (23). Sandia National Laboratories is operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin and is a contractor for the U.S. Department of Energy's National Nuclear Security Administration. Sandia National Laboratories has an Infrastructure Security program whose mission is to develop and apply "technologies and analytical approaches to secure the nation's critical infrastructure against natural or malicious disruption". Within this program is the National Infrastructure Simulation and Analysis Center (NISAC) which is co-run with the U.S. Department of Homeland Security and Los Alamos National Laboratory. The NISAC mission is to "provide strategic, multidisciplinary analyses of interdependencies and consequences of infrastructure disruption…".[5] NISAC has produced the N-ABLE tool which is used to simulate critical infrastructure interdependencies of businesses in the U.S. economy.

Idaho National Laboratory (INL) is operated for the U.S. Department of Energy by Battelle Energy Alliance. Their Critical Infrastructure Protection program performs research, conducts training and develops technologies in modeling and simulation as well as testing, evaluation and demonstration for both physical and cyber security purposes. Two key outputs of the INL include the Critical Infrastructure Modeling Simulation (CIMS) program and the Critical Infrastructure Protection and Resilience Simulator (CIPRSim) framework.

In Italy, the top governmental affiliations are the Institute for the Protection and Security of the Citizens (ISPRA, 30 publications) and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA, 24). ISPRA is one of the seven institutes of the European Commission's Joint Research Centre. Research at ISPRA focuses on, among other topics, internal security and disasters and response. These research areas cover prevention, assessment, risk management and response to intentional, natural and technological disasters on critical infrastructures at the EU level. ISPRA is also a thematic coordinator in the European Reference Network for Critical Infrastructure Protection (ERNCIP).

Within the ENEA is the Unit for Environment and Energy Modeling (UTMEA) which focuses on, among other topics, the security and vulnerability of Italian and European technological networks to natural and human caused disasters. One of the programs within this unit is the Critical Infrastructure Protection and Interdependency Analysis where a number of tools have been developed including MICIE, IRRIIS and DIESIS. New projects of potential interest that are emerging from this group include the Network of Excellence CIPRNet and CockpitCI.

The top academic institutions are dominated by the United States. The Naval Postgraduate School (40 publications) which is home to the Center for Infrastructure Defense focuses on both military and civilian critical infrastructure. The Carnegie Mellon University's (39) Center for Sensed Critical Infrastructure Research (CenSCIR) works on using sensor systems, processes and technologies to collect data on critical infrastructure for improved decision making. CIPR research has also come out of Carnegie Mellon's Software Engineering Institute in the form of OCTAVE (Operationally Critical Threat, Asset and Vulnerability Evaluation) which is a suite of tools for risk-based information security strategic assessment and planning. The University of Virginia's (34) Center for Risk Management of Engineering Systems is an industry and government sponsored research center that has expertise in the areas of risk modeling and assessment, defense and civil infrastructure systems, critical infrastructure protection, preparedness and resilience as well as infrastructure interdependency analysis. Their website includes an extensive list of publications that may be of interest for further research. One Italian university, the Third University of Rome (21, aka Roma Tre University), appears to have CIPR research emerging from its department of Informatics and Automation, in the Faculty of Engineering, although besides seeing this reference on personal Curricula Vitae and doctoral theses in the field, this is hard to confirm as the main website is in Italian and the English website provides extremely limited information.

As was seen in Figure 1 , Canada has a strong showing in the dataset with 84 publications in total. The top Canadian institutions, apart from Defense Research and Development Canada (DRDC), are academic. Figure 4 lists the Canadian affiliations with at least 2 publications.

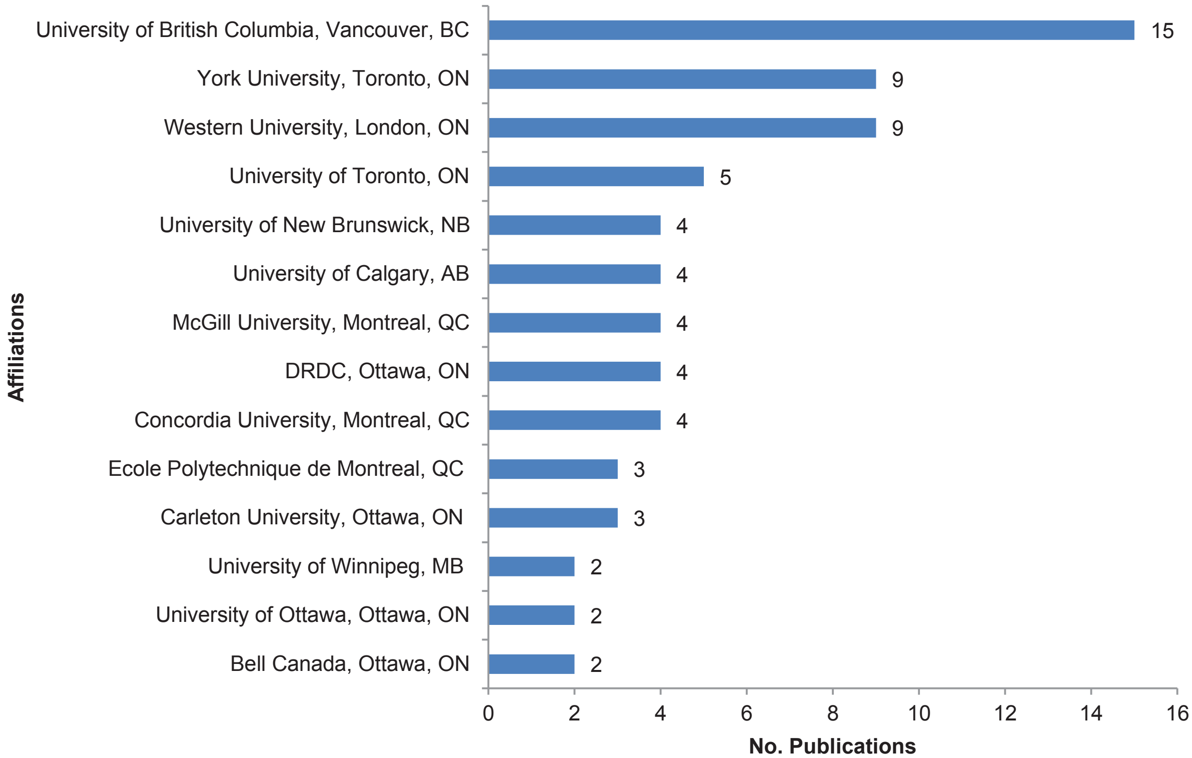

Figure 4. Top Canadian Affiliations in Master Dataset, ≥ 2 Publications, 2003-2013

The pre-eminent Canadian affiliation is the University of British Columbia (UBC) with 15 publications. UBC is one of six Canadian Universities (along with York University, University of Saskatchewan, Ecole Polytechnique de Montreal, University of Toronto and University of Guelph) that were involved in the now completed Joint Infrastructure Interdependencies Research Program (JIIRP) whose goal was to secure Canada's infrastructure from threats and vulnerabilities due to interdependencies. One tool that emerged from the JIIRP at UBC is the Infrastructure Interdependencies Simulator (I2Sim). UBC is also involved in the development of the Disaster Response Network Enabled Platform (DR-NEP) which is a tool for disaster responders and scientific researchers for managing responses to catastrophic disasters. This project is a collaboration between the University of New Brunswick, Western University, the Asian Institute of Technology (Thailand) and the Italian ENEA.

York University (9) was also involved in the JIIRP project. Some of York University's research has emerged from the Department of Earth and Space Science and Engineering (e.g. use of Lidar to map utility corridor objects; use of GIS for spatial analysis of people's vulnerabilities, CI and land use) and the Schulich School of Business (e.g. modeling and simulation of cyber interdependencies between critical infrastructures). York also offers a graduate program in Disaster and Emergency Management.

The University of Western Ontario's (UWO, 9) Engineering Department focuses on, amongst other topics, natural disasters mitigation and management, with numerous facilities or research groups including a Boundary Layer Wind Tunnel Laboratory, Geotechnical Research Centre, Water Resources and Systems Modeling Group and the Institute for Catastrophic Loss Reduction. Other research focuses on infrastructure renewal which includes systems modeling and natural disaster mitigation as well. UWO's role in the DR-NEP is related to the identification of ontological models of its critical Infrastructure and disaster response entities into a common representation as well as the simulation of real-time disasters on its University campus.

Although the Ecole Polytechnique de Montreal is known to be active in the field, it only has 3 publications in the dataset. An additional search was conducted in the main bibliographic databases used in this study to confirm that publications were not missed. A further examination of the website also confirmed that some of the additional publications that are emerging from Ecole Polythechnique's Centre Risque & Performance, are not available through bibliographic databases and therefore did not make it into this report.

4.2.2 Top Affiliations - Interdependency

The top affiliations for the Interdependency set closely resemble the master set albeit with much lower numbers of publications. Figure 5 shows the top 10 affiliations (≥ 7 publications). Because the threshold is lower (≥ 7 as opposed to ≥ 20), a number of new affiliations appear on this list including: Polytechnic University of Milan (Italy), Huazhong University of Science and Technology (China), University Campus Bio-Medico of Rome, Rice University (U.S.), the Italian National Research Council (CNR), TNO Defense (Netherlands) and Gjøvik University College in Norway.

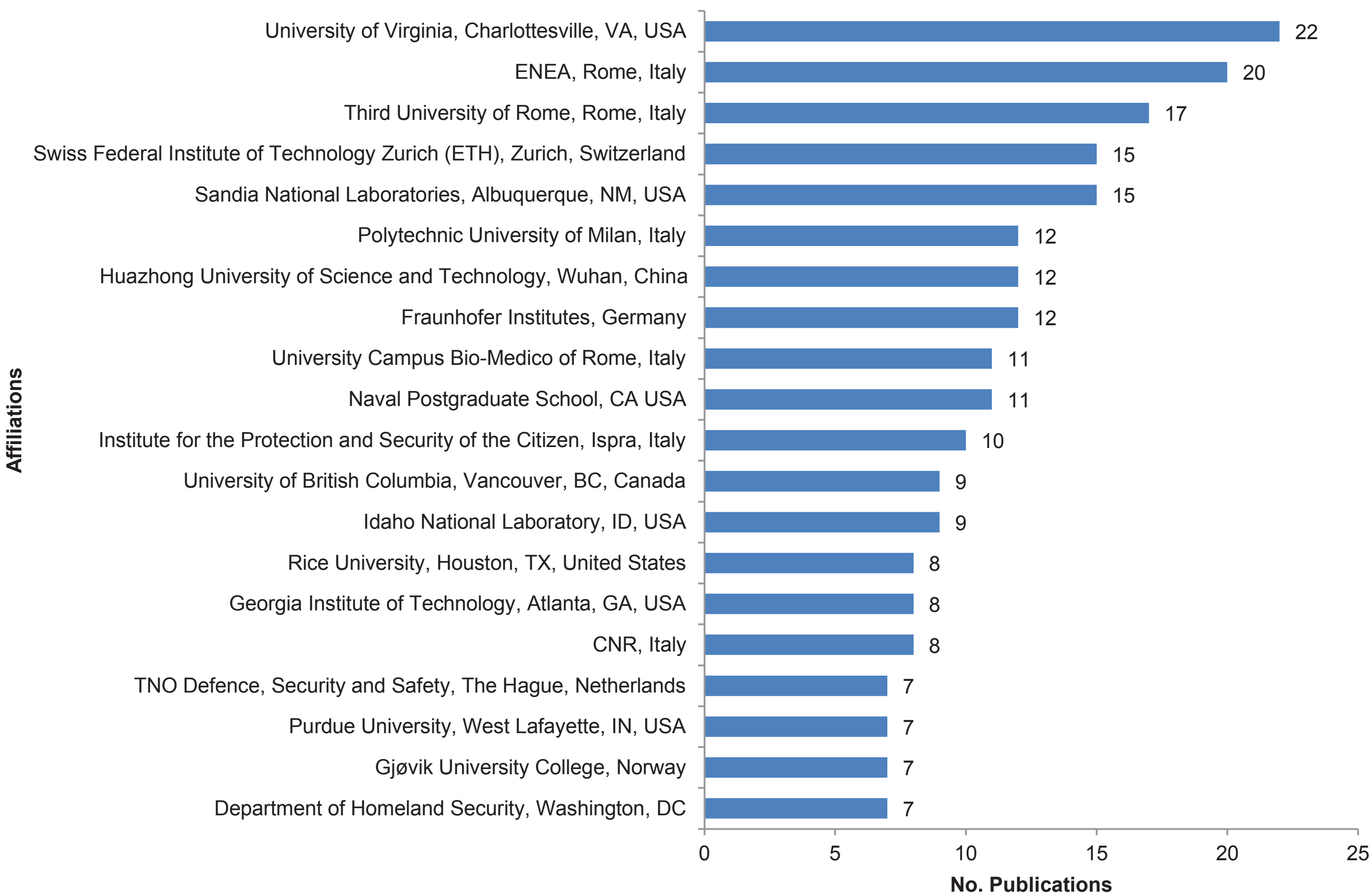

Figure 5. Top Affiliations in Interdependency Dataset, ≥ 7 Publications, 2003-2013

Of particular interest is the University Campus Bio-Medico of Rome (11), which is home to the Complex Systems and Security (COSERITY) Lab, one of the leading Italian research institutes on Homeland Security and Critical Infrastructure Protection. COSERITY is currently focused on interdependency models and fault detection and reaction strategies to cyber and stealth attacks. The Dr. Duenas-Osorio Research Group at Rice University (8) focuses on computational and theoretical models for structure and infrastructure system reliability and risk assessment (SISRRA) in the context of natural hazards, deterioration, and complex operation. TNO Defense (7) is involved in the Critical Infrastructure Preparedness and Resilience Research Network (CIPRNet) and has worked on the DIESIS tool and the Integrated Risk Reduction of Information-based Infrastructure (IRRIS) tool. With DIESIS, TNO Defense is responsible for developing a modeling and simulation tool for dependent CI. With IRRIS, it participated in the development of the Middleware Improved Technology (MIT) software and Simulation for Critical Infrastructure Protection (SimCIP) tool. TNO Defense has co-published a Good Practices Manual for CIP Policies as well as many other CIP related publications.

Figure 6 shows the top Canadian affiliations in the interdependency set. Once again, UBC, York and Western are at the top of the list.

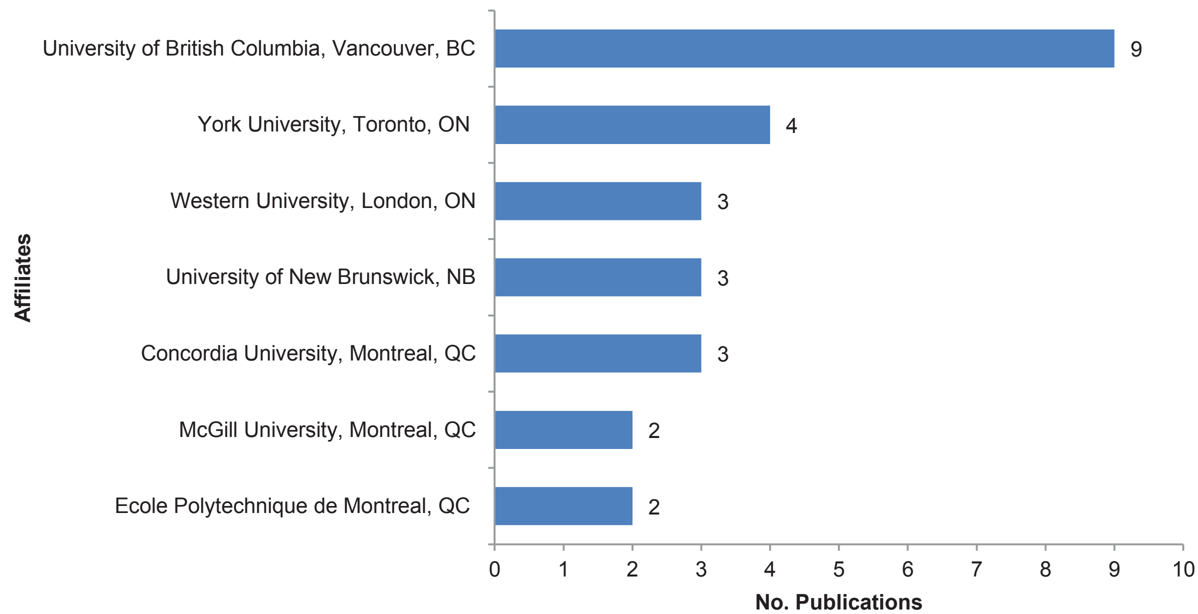

Figure 6. Top Canadian Affiliations in Interdependency Dataset, ≥ 2 Publications, 2003-2013

4.3 Major Topics

As described above, 122 subject groups were created in the master set to group together topics based on terms in the various keyword fields and from words in titles and abstracts. These groupings were created based on a review of the literature in the field, relevant websites, and conversations with the client. 64 of the 122 subject groups were further categorized into four thematic "groups of groups" to enable comparison of groups with similar content and the detection of topics with increasing levels of research in the last five years. The four thematic groups are: *Modeling and Simulation Techniques, Critical Infrastructure, Threats,* and *Government Levels.* These thematic groups are used to drill down into the data to answer the key questions. The development of these thematic groups will be discussed in more detail below.

Cluster analysis based on the co-occurrence of keywords in bibliographic records is one method of visualizing and analyzing topics that are important in a scientific and technical domain as well as their relationships to each other. Figure 7 shows details of the center of a cluster map based on the 122 subject groups created in the project, generated using TouchGraph Navigator[e] software. TouchGraph's clustering algorithm clusters terms together based on statistical similarity to each other (i.e. word co-occurrences) and dissimilarity with other clusters. Generally, a cluster illustrates a self-contained group of concepts that is independent from (though still connected to) the rest of the graph. The size of the nodes in this map represents the relative number of publications associated with each node and the lines in between nodes show the correlation coefficient (multiplied by 100) between two nodes. Only correlations of 21% or greater are shown below.[f]

[e] TouchGraph Navigator is produced by the US company TouchGraph LLC: http://www.touchgraph.com/navigator

[f] Correlation values are set at a percentage that makes the graph readable while still showing a good amount of connection between clusters. It can vary for every map as it is determined through expert judgment as well as trial and error; however 20% is the authors' standard starting point.

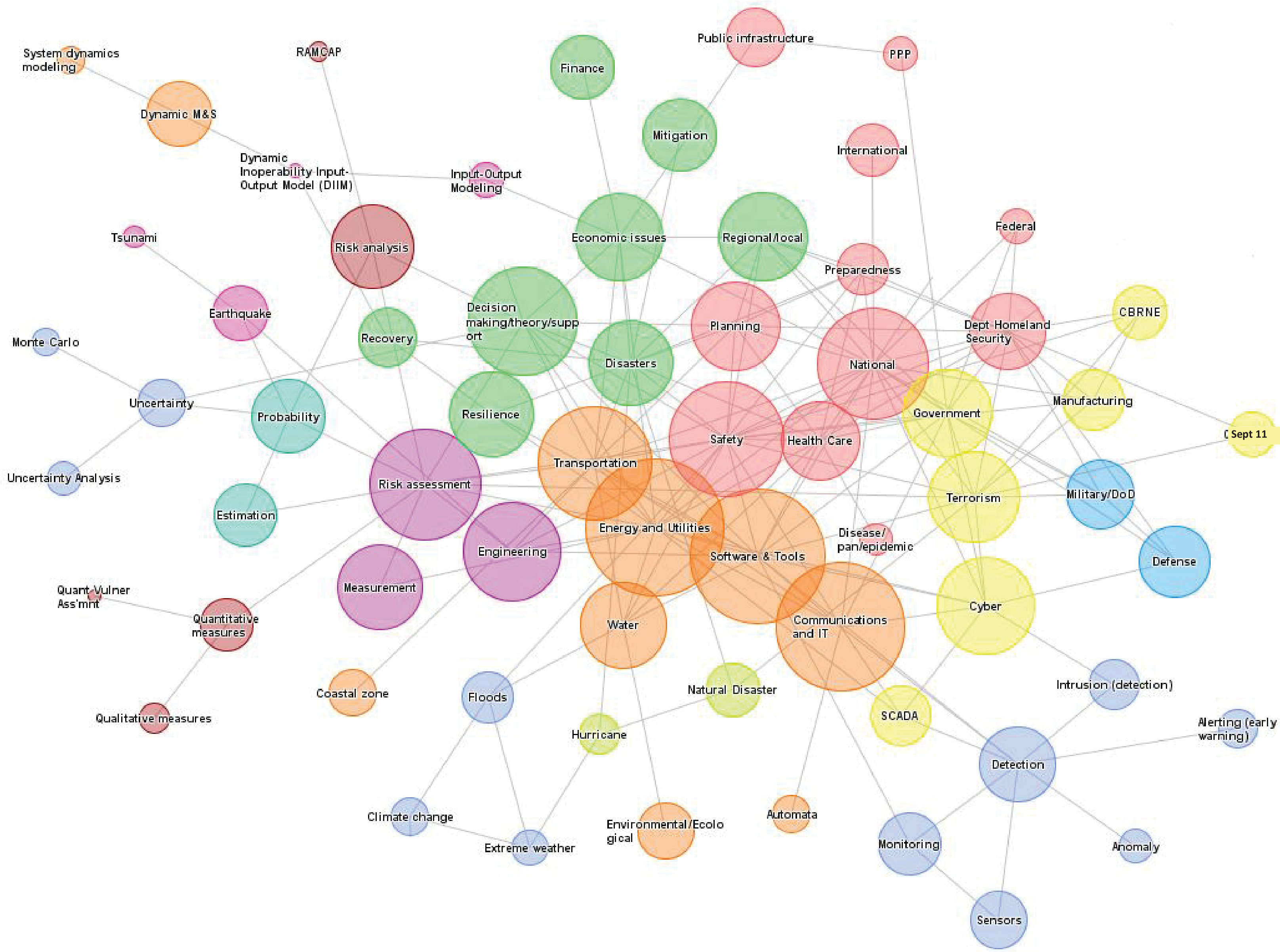

Figure 7. Detail of Cluster map of Master set Subject Groups

The majority of terms on the map fall into one of the four thematic groups and either represent a modeling and simulation technique, a critical infrastructure, a threat or a government body. In addition, we see other higher level concepts related to the field such as can be seen in the bright green cluster which includes resilience, economic issues, mitigation and recovery. Another similar, but smaller, cluster in purple just below includes risk assessment, measurement and engineering.

In the center of this map is an orange cluster representing the largest critical infrastructure groups in the dataset and includes *Energy and Utilities, ICT, Transportation* and *Water.* In the same cluster is *Coastal zones* which correlates with *Transportation* due to ports and the transportation of goods through ports; environmental/ecological topics correlates with *Water*.

Above and to the right is a red cluster that includes *Safety* and *Health Care* (critical infrastructure groups) along with *Disease/pan/epidemic* (a threat to public health and safety) and then two groups, *National* and *Department of Homeland Security* that are categorized into the government thematic category. This is likely occurring because the group *Safety* includes such keywords as public safety, emergency preparedness and management, dams and levees, as well as *CBRNE* related terms.

To the right is a yellow cluster that includes *Cyber*, SCADA, *Terrorism*, *Government*, *Manufacturing* and *CBRNE* and Sept 11. *Manufacturing* includes the chemical industry and the defense industrial base, hence the connection to *CBRNE*.

Many of the nodes further out from the center (not shown in graph) represent the various modeling and simulation techniques that are found in the dataset. While few of them cluster with the critical infrastructure or threats in this map, multiple co-occurrence maps of these techniques will be presented in section 4.3.1 for the master set and section 4.4.1 for the interdependency set further down.

Following the development of the cluster map, the four thematic groups were created in order to gain more insight into how the various modeling and simulation techniques were being used.

A thematic group for the critical infrastructure was created based on the ten Canadian critical infrastructure sectors that are listed in the Canadian *National Strategy for Critical Infrastructure.*[1] Guidance for adding various groups to each of these 10 sectors was gained from the PTSC-Online[g] website[6] and is provided in Table 2 . Additional similar and/or related terms found in the dataset were also added to each CI sector as appropriate.

[g] PTSC-Online is a Canada wide virtual on line community which networks emergency management personnel and emergency services for the purpose of continuously improving the safety and resiliency of our Canadian communities.

Table 2. Canada's 10 Critical Infrastructure Sectors.

CI Sectors	Examples of Components
Energy and Utilities	Electrical power, natural gas, oil production and transmission systems
Information & Communication Technology (ICT)	Telecommunications, broadcasting systems, software, hardware and networks including the Internet
Finance	Banking, securities and investment
Health Care	Hospitals, Health Care and blood supply facilities, laboratories and pharmaceuticals
Food	Safety, distribution, agriculture and food industry
Water	Drinking water and wastewater management
Transportation	Air, rail, marine, surface and mass transit
Safety	Chemical, biological, radiological and nuclear safety, hazardous materials, search and rescue, emergency services and dams
Government	Service delivery, facilities, information networks, assets and key national sites and monuments
Manufacturing	Defense industrial base, chemical industry

In addition to these 10 sectors, the following terms were added to the thematic group due either to their presence in the U.S. list of critical infrastructure sectors or their frequency in the dataset: *Cyber, Buildings, Military, Public infrastructure, Coastal zones*. *Cyber* was given its own group because there were so many publications that focused specifically on cyber issues and less than half co-occurred with *ICT* thus arguably warranting its own examination. *Buildings* was given its own group because they are a physical infrastructure that can fall under threat but did not specifically fit into any other group. While the CI group *Government* does allow for the addition of facilities, key national sites and monuments, many of which are buildings, no specific governmental facilities, sites or monuments were explicitly found in the dataset thus further calling for a CI group to capture the generic buildings found in the set.

Figure 8 displays the number of records between the years of 2003-2012 for each critical infrastructure with the total for each also provided (totals are for 2003-2014). It is important to note that these numbers are not mutually exclusive in that a publication that is categorized in the *Energy and Utilities* sector may also be categorized in the *ICT* sector because the publication discusses both sectors. For instance, 223 of the total 711 *Energy and Utilities* are also found in *ICT.*

Since the overall dataset dropped somewhat in 2012 (as displayed in Figure 1) it is not surprising that the 2012 number of records are slightly lower for quite a few of the sectors. Exceptions include *Energy and Utilities, Safety, Water, Health Care, Military and Public infrastructure* which continue to rise in 2012. *Manufacturing* and, arguably, the *Food* and *Government* sectors show a more notable drop in 2012.

Critical Infrastructure	Total	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
		Year									
Energy and Utilities	711	17	35	47	33	73	54	88	97	113	114
ICT	611	16	41	43	43	62	61	74	85	88	74
Safety	488	13	21	34	36	53	37	46	55	74	84
Transportation	479	11	22	35	30	51	25	62	67	81	73
Cyber	348	11	14	28	23	33	33	38	41	60	53
Government	287	15	19	24	26	33	34	22	32	45	28
Water	285	12	13	18	12	35	14	33	43	36	58
Health Care	232	6	9	14	18	28	26	20	31	31	34
Buildings	172	3	4	11	10	18	6	15	24	36	28
Military	172	9	13	12	7	27	16	10	28	26	27
Finance	151	3	9	16	13	21	27	12	14	16	14
Manufacturing	141	3	12	12	16	23	10	15	19	15	10
Public Infrastructure	129	7	2	12	10	11	11	11	14	15	23
Coastal Zone	82		2	10	6	7	3	12	15	14	11
Food	59	2	4	3	3	6	8	5	10	11	6

Figure 8. Critical Infrastructure Types, Numbers of Publications by Year, 2003-2012

The U.S. Presidential Policy Directive 21 "identifies the Energy Sector as uniquely critical because it provides an "enabling function" across all critical infrastructure sectors".[7] This likely explains the high rates of research and development that we see here. Additionally, the U.S. Department of Energy is the sector specific agency responsible for information sharing and coordination of exercises that address energy infrastructure issues[8] and as was seen in the affiliations section, is ultimately behind much of the CIP research that is emerging from National Labs such as Sandia, Idaho and others. Similarly organizations such as the North American Electric Reliability Corporation (NERC), which is a not-for-profit entity whose mission is to ensure the reliability of the power system in North America (including the United States, Canada and the northern portion of Baja California, Mexico) is very active in CI protection and resilience and has issued numerous reliability and critical infrastructure protection standards.

The *Water* sector has seen fairly steady growth since about 2009 which is shortly after the release of the 2007 *Water: Critical Infrastructure and Key Resources Sector-Specific Plan as input to the National Infrastructure Protection Plan*[9] which set out new R&D priorities for water infrastructure protection. Some of these priorities include: updating identification, prioritization and understanding of physical and cyber threats, and their consequences, along with vulnerabilities to drinking water and wastewater infrastructure; improving analytical methodologies and monitoring systems for drinking water; and addressing infrastructure interdependencies and planning for contingencies.

A second thematic group representing the threats to critical infrastructure was also created. This thematic group was formed by grouping all the threat-related terms that were identified in the 122 subject group creation. A total of 15 threats were identified and the number of records in each year can be seen in Figure 9 (totals include 2013-2014). Again, there is an overall trend to see a slight drop in

2012. Notable anomalies include the significant peak in *CBRNE*-related articles in 2011 (22 as compared to 8 in 2010 and 12 in 2012), as well as for *Climate change* (19 in 2011 as compared to 6 in 2010).

		Year									
Threat	**Total**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Terrorism	308	17	21	38	37	40	30	29	27	36	29
Disasters	263	4	8	16	16	27	18	38	36	46	32
Earthquake	116	4	1	5	6	4	6	17	19	28	20
CBRNE	109	1	4	8	14	9	12	11	8	22	12
Natural disaster	108	3	3	6	7	13	6	15	18	16	11
Floods	96	1	2	1	5	5	6	5	14	21	27
Fire	70	2	2	6	4	9	8	3	7	10	11
Extreme weather	51	1	1	4	3	2	2	4	7	12	11
Hurricane	61			1	4	7	3	9	10	10	10
Blackout	36		1	3	2	6	4	7	3	6	4
Disease/ pan/epidemic	40		3		7	4	5	5	6	4	5
Climate change	52					1	4	5	6	19	12
Denial of service Attack	33		4	1	5	3		2	4	5	6
Tsunami	20			2		1		1	7	5	2
Drought	4							1			3

Figure 9. Master set, Threat by Year, 2003-2012

Given that the threat labeled as *Disasters* is quite vague and all-encompassing with regards to CIPR, a few additional steps were taken to improve clarity. First, an additional group called *Natural disasters* was extracted from the larger *Disasters* group. This group was created by gathering together all terms that explicitly include the words “natural disaster”. Next, a co-occurrence map was run on the *Disasters* group with all the other threats in the dataset to see which specific types of disasters are specified in the *Disasters* group. Figure 10 shows the results and indicates that N*atural disasters* are the most frequently specified type of disaster and is mentioned 70 times in the 263 records that are categorized as *Disasters.* These results show a very similar ordering (based on total number of records) to the main ordering of threats in the master set.

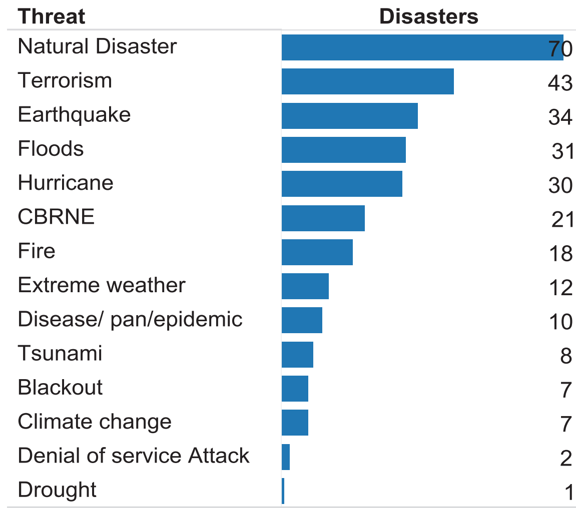

Figure 10. Master set, Number of Co-occurrence between *Disasters* and Remaining Threats

4.3.1 Modeling and Simulation Techniques

The most relevant thematic group in this project is the *Modeling and Simulation* (M&S) group, as the deeper analyses are all based on it. This group comprises 27 different techniques or methodologies found in the dataset that relate to the act of modeling or simulation. These groups were generally formed by grouping the main term (e.g. dynamic) with terms such as analysis, model, simulation, approach, indices, exercise, methods, examples, schemes, as appropriate for each M&S technique. It is important to note that these groups are not mutually exclusive, in that publications that are categorized in the *Dynamic M&S* group may also be categorized in one of the other techniques. For instance, *Dynamic M&S* co-occurs with *System Dynamics Modeling, Estimation, Input-Output Modeling, Agent-based modeling, Classification/Pattern Identification* and *Statistical/Numerical techniques* at least ten times each. The 27 M&S techniques, along with the total number of publications for each, are listed in Table 3.

Table 3. Modeling and Simulation Techniques, Total Number of Publications

M&S Technique	No. Publications	M&S Technique	No. Publications
Dynamic M&S	158	Fuzzy	37
Estimation	145	Behavioral Analysis	33
Statistical/Numerical techniques	124	Bayesian	31
Classification/Pattern Identification	112	Systems Dynamic Modeling	29
GIS	79	Monte Carlo	29
Graph Theory/Model	79	Tree Analysis	26
Topological	68	Clustering	25
Agent-based	60	Petri Nets	19
Input-Output Modeling	47	Markov	18
Hierarchical Methods (other)	45	Network Theory	13
Game Theory	44	Hierarchical Holographic Modeling	8
Uncertainty Analysis	43	Dynamic Input-Output Modeling	8
Forecasting	42	Quantitative Vulnerability Modeling	6
Stochastic Modeling	41		

4.3.1.1 Emerging Research Trends in Modeling and Simulation

In order to identify emerging research trends in the modeling and simulation of CIPR, an R&D momentum analysis was conducted. Further explanation of the methodology behind the momentum indicator is included in Section 7.3, but essentially it plots the standard deviation of standardized measures of publication counts and velocity (the rate of publication increase) on two axes. Nodes which plot to the left of the Y-axis intersection have below-average velocity, and those found below the X-axis have relatively smaller publication counts. A third dimension is added by sizing nodes relative to the total number of underlying publications. Even a small node which plots to the right/lower side of the axes may be of interest, since emerging topics are typically small in numbers as they begin to attract research attention and increase in velocity. Figure 11 plots the momentum of all 27 modeling and simulation techniques.

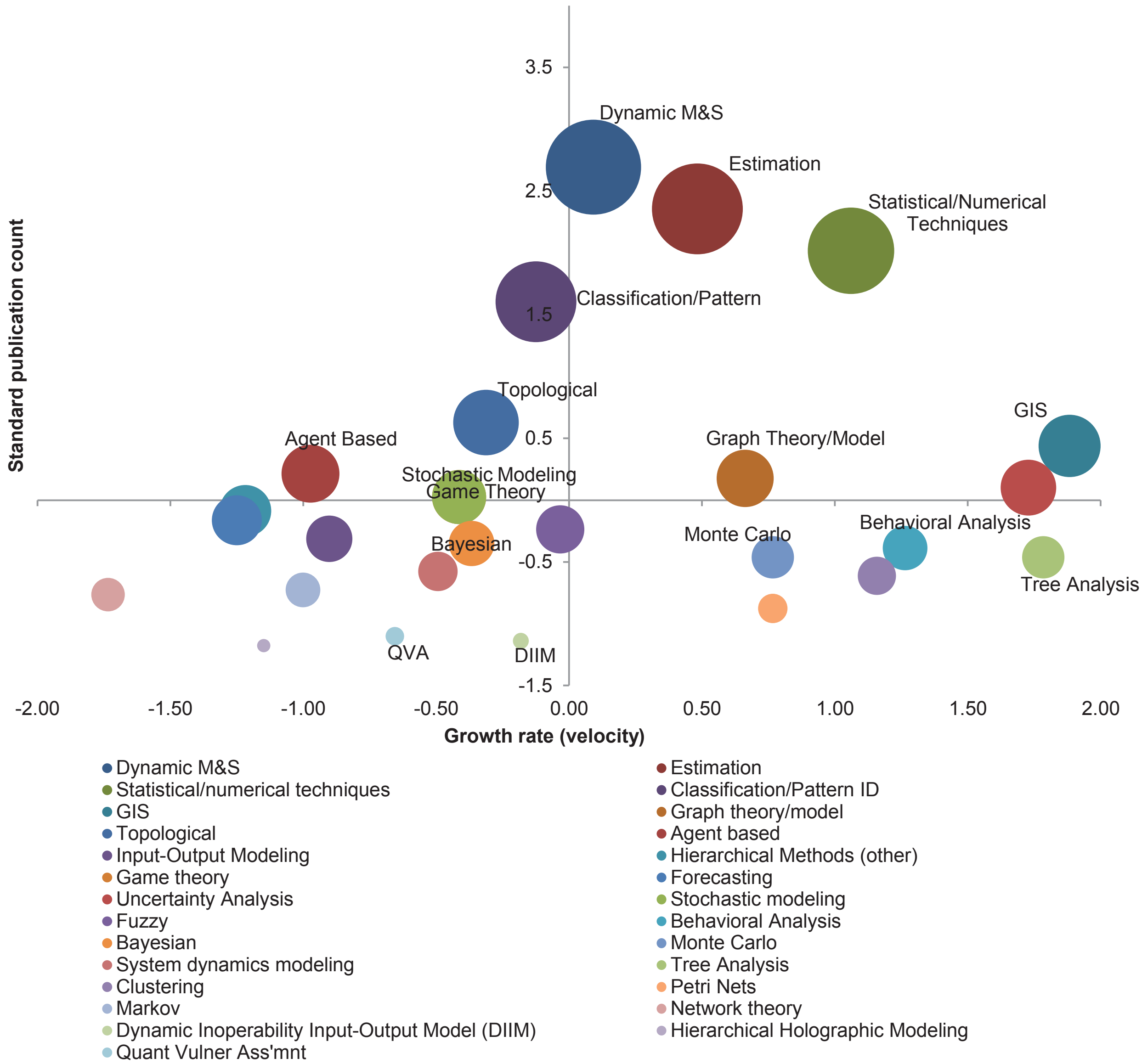

Figure 11. R&D Momentum, Modeling and Simulation Techniques, Master Set, 2008-2012[h]

The majority of M&S techniques fall on or below the x-axis. M&S that are already "hot" in the field with high number of records and a high rate of acceleration include *Dynamic M&S, Estimation, Statistical/numerical techniques, GIS, Graph theory/model* and *Uncertainty analysis*. Established trends in the field can be seen in the use of *Classification/pattern analysis, Topological and Agent-based* techniques. In order to assess whether the remaining M&S are brand new (in terms of application in the field of CIPR), disappearing or emerging topics in relation to CIPR, the number of publications in each node in the lower quadrants is presented for the past 5 years.[i]

[h] Note that Game Theory and Stochastic Modeling show up in the exact same place (large green and orange circle at X, -0.5, Y, 0).

[i] The R&D momentum and the figures 11-13 are based on data between 2008 and 2012 because 2013 was not a complete year at the time of data collection and would throw off the growth rates if included.

Figure 12 presents the M&S nodes found in the lower left quadrant, which is where the “new” or “disappearing” techniques in the field are typically found. Keeping in mind that the overall master set saw a drop in number of records in 2012, there are a number of things to point out. The steadiest growth can be seen in the use of *Bayesian* techniques. *Bayesian* techniques have been used in the development of a framework for assessing risk probability with a particular focus on information systems,[10] in the use of max-propagation in a Bayesian networks to identify critical components in infrastructure systems,[11] in the development of a terrorist activity prediction model (TAPM) using Dynamic Bayesian Network (DBN)[12] and as a novel approach to CI interdependency analysis based on DBN formalism[13] to name just a few. *Fuzzy* techniques may also be rising as there is a peak in 2011 but more data would need to be seen over time to confirm this. *DIIM* and *Quantitative Vulnerability Assessment* (QVA) appear to be more on the end of disappearing rather than brand new.

			Year		
Modeling and Simulation Technique	**2008**	**2009**	**2010**	**2011**	**2012**
Bayesian	1	5	4	6	8
Dynamic Inoperability Input-Output Model (DIIM)		1			2
Forecasting		12	4	8	5
Fuzzy	3	3	6	10	5
Hierarchical Holographic Modeling	1		1		
Hierarchical Methods (other)	4	7	9	6	5
Input-Output Modeling	5	4	8	2	6
Markov	2	5	1	2	4
Quantitative Vulnerability Assessment	2			2	
System Dynamics Modeling	1	3	4	6	4

Figure 12. Master Set, Modeling and Simulation Techniques by Year, Nodes in the Lower Left Quadrant – New or Disappearing Techniques.

Figure 13 represents the M&S techniques that fall in the lower right quadrant, or the “emerging” techniques quadrant. Most notably we can see a doubling in the use of *Behavioural Analysis* and *Monte Carlo* techniques for modeling or simulating CIPR in the last 2 years and a significant jump in *Tree Analysis* in 2012.

			Year		
Modeling and Simulation Technique	**2008**	**2009**	**2010**	**2011**	**2012**
Behavioral Analysis	1	6	4	4	8
Monte Carlo	1	3	2	5	10
Tree Analysis	1	4	3	1	12
Clustering	1	4		7	5
Petri Nets		1	3	2	4

Figure 13. Master Set, Modeling and Simulation Techniques by Year, Nodes in the Lower Right Quadrant – Emerging Techniques.

Behavioral analysis can be used to study reduction in risk as a result of changing behaviors prior to an event, for studying anomalous behaviors, or in predicting terrorists' behavior. *Behavioral analysis* has been used to increase the resilience of SCADA systems,[14] cyber threats,[15] and a novel application of Evidential Reasoning to Threat Assessment.[16] *Monte Carlo* techniques have been used as part of a Fuzzy Monte Carlo Simulation approach to study smart grids[17] in seismic modeling[18-20] and in the Sandia developed Scenario Toolkit and Generation Environment (STAGE) simulation engine.[21] A number of the 2012 articles on *Monte Carlo* techniques also mention a tree analysis technique.[18,22,23] Most notably, *Tree analysis* jumped significantly in 2012 with 12 records as compared to a high of four in 2009. This may indicate that there was a recent breakthrough in the use of tree analysis. Vintr, Valis and Malach explain that attack tree-based evaluation of vulnerability is an analytic method that has been dynamically developed and has recently had its theoretical boundary conditions for practical applications worked out.[24] Attack tree, fault tree or regression tree analysis have been used in Probabilistic Seismic Hazard Analysis,[25,26] drinking water treatment plants,[27] dam security models,[28] the Florida Public Hurricane Loss Model,[29] and safety of railway tunnels[22] to name a few.

4.3.1.2 M&S and Threats

To further explore the modeling and simulation techniques that are discussed in the dataset a co-occurrence table was created to cross reference the M&S techniques with the threats that were presented in Figure 9. Figure 14 identifies which technique is most frequently used with each threat. Some notable points that can be seen in this figure include the fact that *Dynamic M&S* is most frequently used in modeling *Disasters (28), Earthquakes (22), Natural disasters (19) and Terrorism (17)*. *Dynamic M&S,* represents a group of general modeling or simulation techniques that are referred to as dynamic when they incorporate time-dependent parameters.[30] *Estimation* is most frequently used for *Floods* (23) with *Earthquakes* (16), *Terrorism* (15) and *Climate change* (13). In fact, *Estimation* is the most frequently used technique for all of *Flood* AND *Climate change* modeling. *Estimation* may be used to model risks, vulnerabilities, reliability, costs, damages or loss etc... *GIS* is most frequently used for *Disasters* (27), *Floods* (15), *Fire* and *Terrorism* (10 each). *GIS* is the most frequently used method for all *Fire* modeling. *GIS* is used in a variety of ways and sometimes in combination with other M&S techniques to include a geospatial understanding of critical infrastructure vulnerabilities and risk prevention. For example, a GIS-based software application called E3R was created to merge the needs of risk assessment, risk reduction and risk management during different phases of disaster response into a single tool.[31] A *GIS* based macro-simulation model was developed to support evacuation planning and training in the event of a terrorist attack on sports stadium.[32] *GIS* was also recently used in a Canadian study to create vulnerability indicators based on spatial and attribute data related to human vulnerability, critical infrastructure and land use.[33] *Statistical/numerical techniques* are used most for modeling *Disasters* (17), *Terrorism* (13) and *CBRNE* (13). Once again, *Statistical / numerical techniques* is the most frequently used technique for all of *CBRNE* and *Disease/pan/epidemic* modeling. One interesting outlier to draw attention to is the disproportionate uses of *Game Theory* (15) in *Terrorism* modeling. These 15 records are relatively evenly dispersed across the timeframe of the study. These records discuss, amongst other topics, the use of *Game Theory* to model cyber-attacks,[34] to model or simulate terrorist attacks on transportation networks,[12,35,36] to monitor pipelines against terrorist attacks,[37] and as an Adaptive Two-Player Hierarchical Holographic Modeling (HHM) Game to track terrorism scenarios.[38]

Modeling and Simulation Technique	Disasters	Terrorism	Earthquake	Floods	Natural disaster	CBRNE	Hurricane	Climate change	Extreme weather	Fire	Blackout	Disease/ pan/ epidemic	Denial of service Attack	Drought	Tsunami
	Threat														
Dynamic M&S	28	17	22	8	19	9	8	3	8	6	3	1	2	1	1
Estimation	13	15	16	23	8	9	6	13	7	3	3	2	2	2	2
GIS	27	10	9	15	8	6	4	3	5	10		1	1		2
Statistical/numerical techniques	17	13	11	11	5	13	5	6	4		2	7	1	2	1
Classification/Pattern ID	13	13	7	4	5	8	5	4	4	1	3	1	2	1	1
Input-Output Modeling	14	10	2	2	10	1	3	1	1		1		1		
Uncertainty Analysis	4	6	9	6	2	2	5	4	2					1	
Topological	8	5	4		1	1	3			3	3	3	3		
Graph theory/model	7	6	4	4	2	1				3	2	2	1		
Agent based	6	6	5		1	3	1			2	3	1	1		
Stochastic modeling	7	3	4	1	4	1	1				3	3		1	
Forecasting	2	4	1	5	1	1	2	4	4				2	1	
Game theory	3	15			3	1	1		1				3		
Bayesian	2	3	2	2	1	1	3	5	2	1		1	1	1	
Monte Carlo	4	3	6	1		6	1	1	1	1	1				
System dynamics modeling	7	2	2	2	3	1	3	1	3	1					
Hierarchical Methods (other)	6	5	2		4	1	1				2	1			1
Behavioral Analysis	4	4	2	1	1	3	1	1		2			1		
DIIM	7	2	1	1	6		1						1		
Clustering	1	6	1			2		1		3	1	2			
Network theory	3	2	2	1	2		2	1	1		1				
Fuzzy	3	4	2	1		1		1		1					
Markov	2	1	1	2	1	2			1		1				
Tree Analysis		3	3	2			2	1							
Petri Nets	1			2	1						1	1			
Hierarchical Holographic Modeling		4			1										

Figure 14. Modeling and Simulation Techniques by Threats, Numbers of Publications

4.3.1.3 M&S Techniques for Specific Critical Infrastructure Types

Figure 15 presents a co-occurrence matrix of M&S techniques with the critical infrastructure types presented in Figure 8. The most frequently used technique for each CI is listed in Table 4.

Table 4. Most Frequently Used M&S for each Critical Infrastructure

Critical Infrastructure	M&S Technique (No. pubs)
Energy and Utilities	Dynamic M&S (51), Estimation (50)
ICT	Dynamic M&S (46), Classification/Pattern ID (38)
Transportation	Dynamic M&S (41), Classification/Pattern ID (27)
Safety	Estimation (45)
Water	Estimation (29)
Cyber	Classification/Pattern ID (20)
Health Care	Statistical/numerical techniques (18)
Buildings	Dynamic M&S (24), Classification/Pattern ID (13)
Finance	Dynamic M&S (13) Input-Output Modeling (10)
Government	Dynamic M&S (9), Forecasting (9), Classification/Pattern ID (9)
Manufacturing	Dynamic M&S (12), Estimation (9)
Military	Statistical/numerical techniques (9)
Public Infrastructure	Dynamic M&S (9), Estimation (9), GIS (9)
Coastal zone	GIS (11)
Food	Dynamic M&S (4), Estimation (4), Classification/Pattern ID (4)

As can be seen in Table 4, *Dynamic M&S* is the top modeling and simulation technique for many of the critical infrastructure in this study. Outside of the top 5 techniques used by all the critical infrastructure, including *Dynamic M&S* (158), *Estimation* (145), *Statistical/numerical techniques* (124), *Classification/pattern identification* (112) and *GIS* (79) along with the prevalence of each technique in *Energy and Utilities* (which has the greatest number of records in total) there are some other interesting observations that can be made from Figure 15. In particular there is a significant use of *Topological* methods (40) in *Energy and Utilities* and *ICT* (33) and of *Hierarchical methods* (22) used in *ICT*. *Topological* methods can be considered as a type of network based methods that do not consider node heterogeneity, whereas *Hierarchical methods* model risks or vulnerabilities from a levels perspective. *System Dynamic Modeling* (12), which, like *Dynamic M&S,* models complex systems over time, is most frequently used by *Safety*. *Behavioral analysis* is most frequently used by *Transportation* (9) and *Energy and Utilities* (9). *DIIM*, which seems to be mentioned very rarely with a specific critical infrastructure, is seen most frequently within *Finance* (2).

Modeling and Simulation Technique	Critical Infrastructure														
	Energy and Utilities	ICT	Transportation	Safety	Buildings	Water	Health Care	Cyber	Finance	Manufacturing	Government	Public infrastructure	Coastal zone	Military	Food
Dynamic M&S	51	46	41	34	24	22	14	13	13	12	9	9	7	5	4
Estimation	50	21	26	45	11	29	14	11	8	9	8	9	8	8	4
Statistical/numerical techniques	39	33	21	33	10	21	18	7	6	6	7	4	2	9	3
Classification/Pattern ID	28	38	27	19	13	13	9	20	9	6	9	8	6	7	4
GIS	21	15	21	31	12	25	16	1	2	4	7	9	11	3	3
Graph theory/model	34	26	18	9	3	5	4	10	1	3	4	1	3	3	
Topological	40	33	10	6		5	1	8	3		3	1	1	3	
Agent based	26	21	14	8	5	5	6	11	9	5	3	1	4	4	2
Input-Output Modeling	11	9	8	3	1	1	4	6	10		3			2	1
Hierarchical Methods (other)	18	22	10	7	5	5	4	9	4	4	4	4	1	2	2
Game theory	20	10	14	5	1	7	2	8	4	1	2	4	2	6	1
Uncertainty Analysis	16	4	8	8	2	10	1	2	1	3	1				3
Forecasting	14	10	10	5	4	5	2	5	3	2	9	3	1	3	
Stochastic modeling	14	13	8	8	1	3	1	3	4	3	3	5	1	4	
Fuzzy	12	5	8	6	4	4	4	6	4	1	3	2		1	
Behavioral Analysis	9	7	9	5	4	3	1	7	2	2	4	2	2	2	2
Bayesian	11	4	11	7	2	3	4		1	1	1		1		2
System dynamics modeling	6	9	7	12	8	6	5	3	3	2	6	2		3	
Monte Carlo	12	2	6	9	2	5	2		7	2	1	4		1	
Tree Analysis	11	5	6	7	1	4	1	4	1	2	1		1		
Clustering	6	9	7	6	3	5	5	4	3	2	3	2	2	3	2
Petri Nets	9	5	2	1	1	3		4			1	1	1	1	
Markov	7	4	3	1		3		2					1		
Network theory	9	5	5	2	1	2		2			2		1		
Hierarchical Holographic Model..	2	2	3			1	1	3	3	1					3
DIIM	1	1					1		2		1				
Quant Vulner Assessment	1														

Figure 15. Modeling and Simulation Technique by CI Type, Master Dataset

4.3.1.4 M&S Techniques by Government Level

Another way to explore modeling and simulation techniques in the data set is to examine who is using each M&S. Instead of analyzing the "who" on an individual basis, a fourth thematic group called "*Government*" was created to group together the main user groups in the dataset. The *Regional/local* group was made by gathering all terms with the words "regional" or "local" in them. The top terms include local government, regional planning, regional level, local level, regional/local infrastructure etc. The *National* group includes national infrastructure, national capital region, as well as federal government and federal agencies. *Government* includes the term government, government agencies, government services, government sector, as well as various international governments as in U.S., U.K., Hong Kong, Chinese, Dutch, etc. The *Department of Homeland Security* is created by grouping together all terms that refer specifically to homeland security (e.g. DHS, policy, agencies, analysts, modeling, operations, directives etc.). *Military/DoD* differs only slightly from the *Military* CI group in that it includes the Defense Industrial Base (which is found in the *Manufacturing* CI Sector). *International* groups together various terms in conjunction with the word 'international' (such as relations, trade, level, infrastructure networks) and also includes the United Nations and terms in conjunction with the word transnational.

Figure 16 shows the co-occurrence of each of these government bodies with the modeling and simulation techniques. This map has the modeling and simulation techniques ordered by most frequent co-occurrence across all groups (i.e. *Dynamic M&S* is used most across all 6 government bodies, followed by *Estimation* etc.) The first 3-5 techniques are used quite regularly by each government body. *Input-Output modeling*, *Uncertainty analysis* and *Bayesian* techniques are used most frequently by the *Regional/local* group, whereas *Agent based* modeling is used most by the *National* group. The *Government* group uses *Forecasting* more than any other M&S, while the *Military* uses *Game Theory* more often than *Dynamic M&S*.

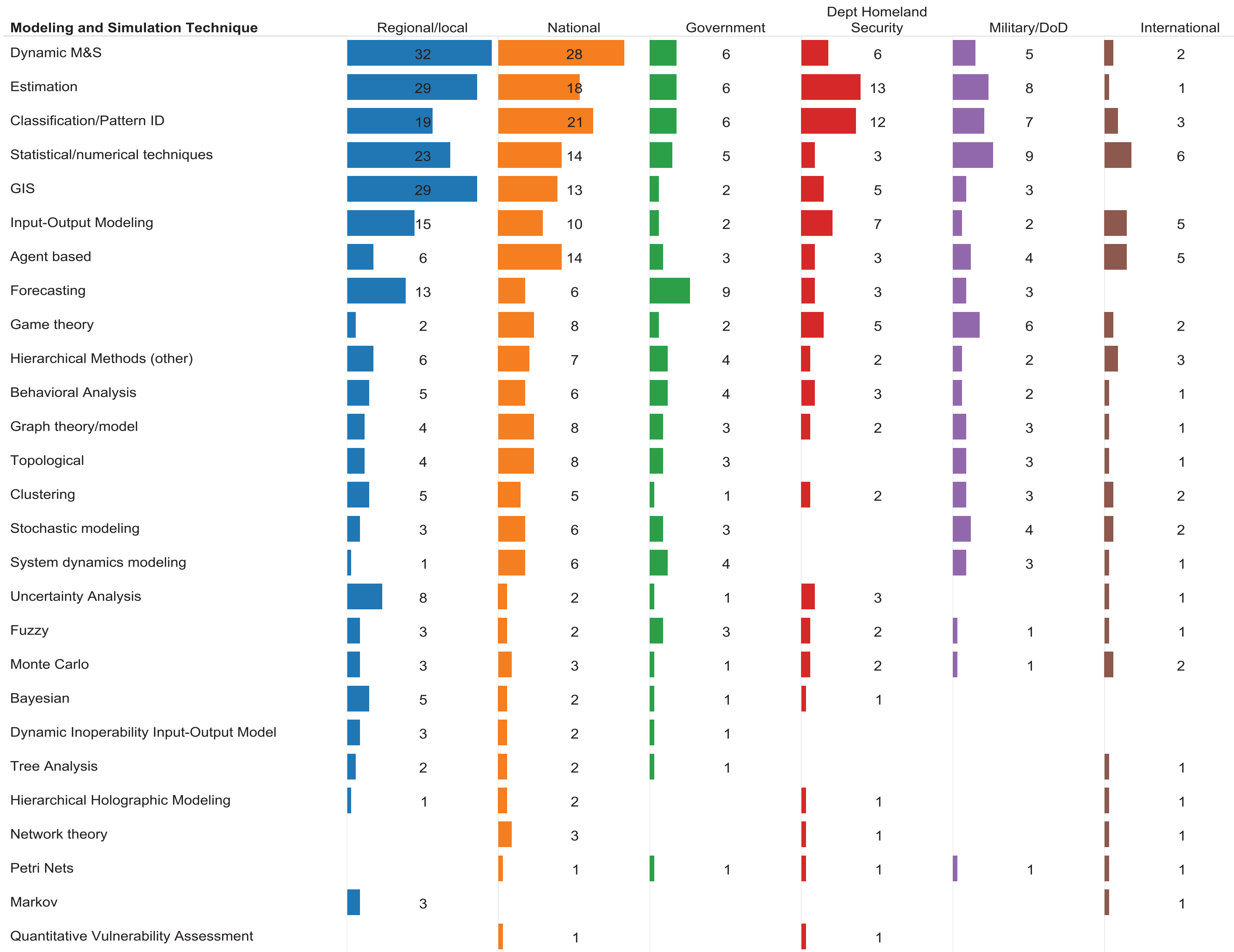

Figure 16. Modeling and Simulation Technique Usage by Government Levels, Master set

4.4 Interdependency Topics

Interdependency modeling of critical infrastructure is an important and growing field of study[2,4]. Recent worldwide events such as 2001 World Trade Center attacks, Hurricane Katrina and Sandy, the 2011 earthquake in Japan and the 2013 typhoon in the Philippines, as well as other disasters, have shown us that interdependencies between critical infrastructures are complex and can result in cascading failures. Interdependencies may be in the form of physical, cyber, geographic or logical dependencies.[39] Modeling these interdependencies is a critical step in identifying the real vulnerabilities of infrastructures and protecting them. Much like general CI modeling and simulation there are many different approaches as will be reviewed below. Ouyang[2] provides a good overview of interdependency typologies as well as a helpful categorization and comparison of various modeling and simulation approaches in the CI interdependency literature. That being said, there are multiple ways in which these models are related and there is no single taxonomy or classification that suits all purposes.[40]

As mentioned earlier, the Interdependency set was created by extracting all records that had the term interdependency, independency, dependent, dependency, regional, or local, and totalled 633. All figures and tables in this section, unless otherwise specified, are based strictly on the 633 record Interdependency set. All of the analyses that were performed on the master set are repeated for the interdependency set in order to focus in on the specific topic of modeling and simulating critical infrastructure interdependencies.

As described above, the same 122 subject groups were also used in the interdependency set to group together topics based on terms in the various keyword fields and from words in the title and abstracts. The same four thematic groups of *Modeling and Simulation Techniques, Critical Infrastructure, Threats,* and *Government Levels* were also used to drill down into the data to answer the key questions.

A subset of the cluster map of the 122 subject groups is provided in Figure 17. The largest red cluster includes many of the CI groups including *Safety, Health Care, Government, Military, Cyber, Manufacturing* with many of the threats e.g. *Disasters, Terrorism, Hurricane, CBRNE, Disease/pan/epidemic* and all six of the terms in the *Government* thematic subject group: *Regional/local, National, Government, Military/DoD, Department of Homeland Security and International*. More general words that also cluster in this group are mitigation, planning, preparedness and SCADA.

Next there is a large yellow cluster in the center of the map that groups the largest critical infrastructure groups including *Energy and Utilities*, *ICT*, *Transportation*, and *Water* with *Finance*, and *Coastal zones*. This cluster also includes software & tools, resilience, recovery, and economic issues. The inclusion of software & tools in this cluster makes sense since these CI groups are the predominant users of the tools found in the dataset.

As in the master set, we see a clustering of risk assessment, measurement and engineering in blue next to the yellow cluster. These are again connected to risk analysis which is clustered with RAMCAP (Risk Analysis and Management of Critical Asset Protection) in brown, qualitative measures, quantitative measures and quantitative vulnerability assessment in green, *Estimation* and probability in orange, *Uncertainty* and *Monte Carlo* in bright green as well as *Tsunamis* and *Earthquakes* in pale green.

Below the yellow set is a purple cluster bringing together detection, anomaly, intrusion, sensors, monitoring and alerting (early warning). While above the yellow set is a blue cluster including *Floods, Climate change* and *Extreme Weather* which correlates with the adaptive and adaptation cluster in purple. There is also a turquoise cluster just to the right of this one that brings together a number of modeling techniques including *Dynamic M&S*, *Input-Output modeling*, *DIIM*, and *System Dynamics Modeling.*

Many of the remaining nodes that are further out from the centre (not shown here) are the modeling and simulation techniques as well as threats in the dataset. While the M&S are not all clustering with the various CI groups, we will repeat the same analyses as above to explore the relationships between the M&S and CI, M&S and threats and M&S and government levels in section 4.4.1.

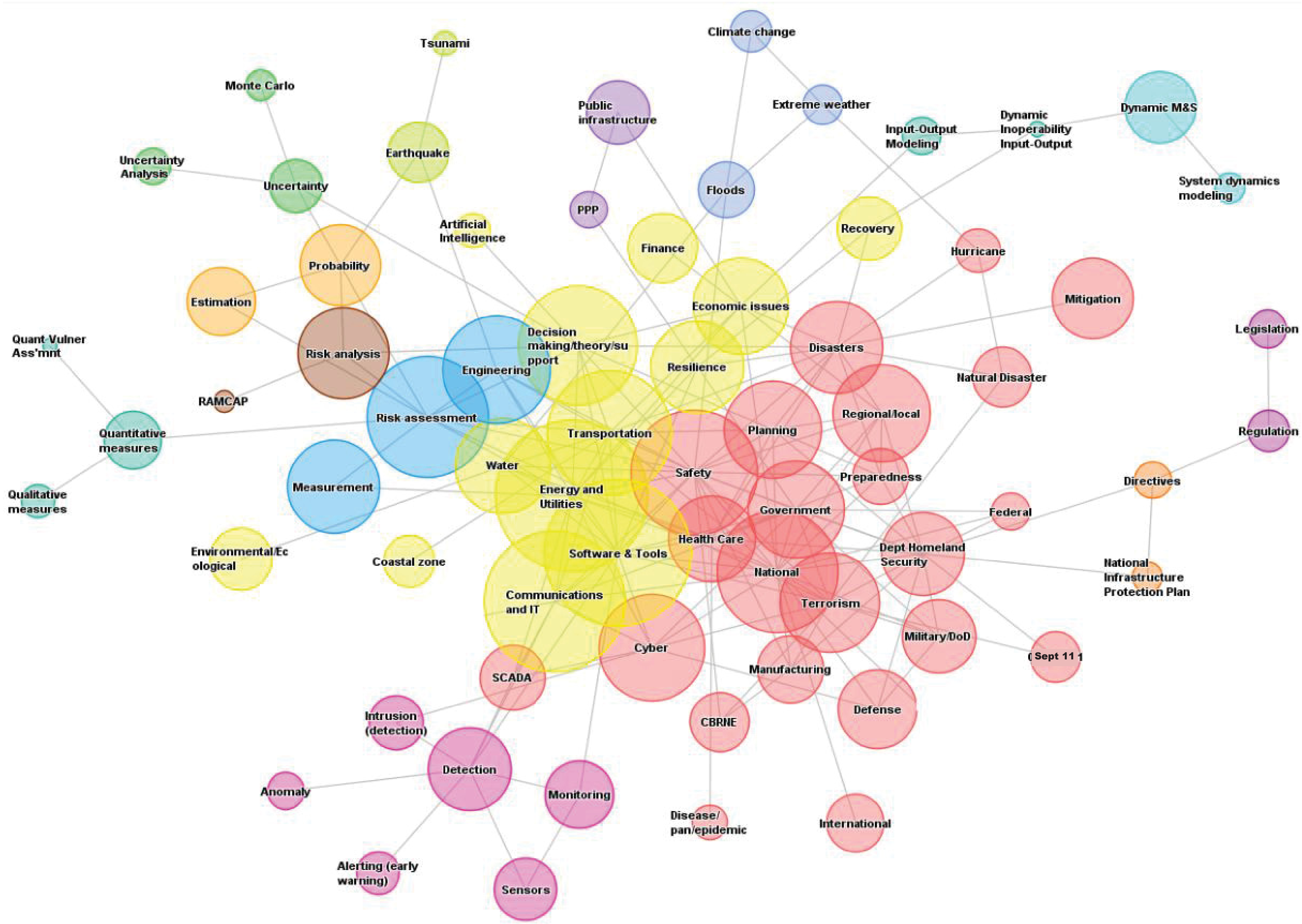

Figure 17. Cluster map of Interdependency set subject groups

Figure 18 presents the number of records by year for each critical infrastructure as well as the totals for the time period (2003-2014). Since the interdependency set did not have as significant a drop in 2012 as compared to the master set, overall we do not see as much of a drop in records in 2012 for the various sectors. Once again *Energy and utilities* is top of the list. This is unsurprising since virtually all industries are reliant on power and fuel and communities are reliant on utilities, all the other sectors have some dependence on this sector.[8] Some notable drops include *Government*, which had been steadily climbing since 2009, but dropped by more than half (from 15 to 7) in 2012. *Cyber* also dropped by 50% between 2011 and 2012, and *Food* dropped from 4 to 1 between the same years. On the other hand we do see some growth in a few sectors despite the drop in overall records: *Safety* grows from 17 to 20 in 2012 and *Water* nearly doubles from 8 to 15. Another observation that can be made by comparing the two sets is that *Safety* and *Transportation* have switched place. More significantly, there are relatively more interdependency modeling and simulations publications in the *Water* sector (now in 5th place in the interdependency set as opposed to 7th in the master set) and less in *Cyber* (which has gone from 5th place in the master set, to 9th in the interdependency set). This rise in the position of the *Water* sector may be due to the great number of interdependencies that exist between water infrastructure and many of the other CI sectors including *Safety* (firefighters), *Health Care, Energy and Utilities, Transportation* and *Food.*[41]

		Year									
Critical Infrastructure	**Total**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Energy and Utilities	250	4	12	17	8	36	19	38	33	34	32
ICT	190	2	11	12	17	21	19	30	29	23	16
Transportation	168	2	10	12	10	21	6	25	29	24	21
Safety	148	1	7	14	10	20	13	18	16	17	20
Water	105	3	6	6	4	17	5	19	17	8	15
Health Care	79	2	2	5	7	14	6	8	12	11	9
Government	76	1	5	8	5	6	3	9	13	15	7
Military	67	2	3	7	1	5	6	9	13	8	7
Cyber	66	1	1	4	5	9	6	8	11	12	6
Finance	53	2	5	4	3	8	13	5	6	1	4
Buildings	49		1	5	5	9		6	7	9	7
Manufacturing	40		4	2	3	6	3	4	9	5	3
Public infrastructure	29	2		2	2	3	3	3	4	3	2
Food	24	1	2	1		2	5	2	5	4	1
Coastal zone	22			3	4		1	5	4	2	2

Figure 18. Interdependency set, Critical Infrastructure by Year, 2003-2012 (Totals based on 2003-2014.)

The same threats from the master set were also mapped out in the interdependency set. Figure 19 shows the number of records in each year between 2003 and 2012 along with the totals for 2003-2014. Notable changes in this figure, as compared to the master set, is that *Disaster* interdependency modeling and simulation now surpasses general *Terrorism* modeling and simulation (first in the master set based on total records between 2003-2014). Similarly, if we look just at the number of records in 2012, *Terrorism* drops from 2nd in the master set to 3rd in the interdependency set, whereas *Earthquake* moves from 4th to 2nd. *CBRNE* has also dropped from 4th place to 8th based on total records between

2003 and 2014. This all shows that there are slight shifts in the threat areas that dominate the interdependency modeling and simulation literature.

		Year									
Threat	Total	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Disasters	115	2	4	8	5	18	9	21	13	13	14
Terrorism	82	1	5	13	7	11	6	9	12	8	6
Earthquake	55	2		3	2	3	2	12	7	11	8
Natural Disaster	45	1	2	4	2	9	3	6	3	4	6
Floods	33	1		1	2	5	3	2	6	5	5
Hurricane	28			1	1	7	2	5	2	4	4
CBRNE	23		1	3	1	2	3	3	1	6	1
Blackout	24		1	1		4	3	6	1	5	2
Fire	23			3		5	4	1	3	3	4
Extreme weather	19			3	2	2		4	3	2	3
Climate change	19					1		2	4	4	5
Disease/ pan/epidemic	10				2	2	1	1	3		
Denial of service Attack	6				1			1		1	2
Tsunami	7							1	3	1	
Drought	1										1

Figure 19. Interdependency set, Threat by Year, 2003-2012

As in the master set, a *Disasters* co-occurrence map was made to see which specific types of disasters are most frequently studied in the interdependency set. Figure 20 shows that the majority of disasters are virtually the same as in the master set with *Natural disasters, Terrorism, Earthquake and Floods* topping the list. The only small difference is that *Blackout* has risen to roughly the midpoint whereas it was much closer to the bottom of the list in the master set. Perhaps this is due to the fact that on its own, *Blackouts* are not as significant a threat to critical infrastructure as it is when you take into account the cascading effects it has on other sectors.

Threats	Disasters
Natural Disaster	27
Terrorism	20
Earthquake	16
Floods	14
Hurricane	14
CBRNE	6
Blackout	6
Fire	5
Extreme weather	5
Disease/ pan/epidemic	4
Tsunami	2
Climate change	2
Denial of service Attack	1
Drought	1

Figure 20. Interdependency set, Co-occurrence of Disasters with Remaining Threats

4.4.1 Interdependency Modeling and Simulation

The same 27 modeling and simulation techniques from the master dataset were examined in the interdependency set. Table 5 presents the total number of records for each in this subset. As in the master set, *Dynamic M&S* is at the top closely followed by *Estimation*.

Table 5. Modeling and Simulation Techniques, Interdependency set, Number of Publications.

M&S Technique	No. Publications	M&S Technique	No. Publications
Dynamic M&S	65	Clustering	10
Estimation	52	Stochastic modeling	10
GIS	39	System dynamics modeling	10
Input-Output Modeling	38	Behavioral Analysis	9
Classification/Pattern Identification	36	Monte Carlo	9
Statistical/numerical techniques	35	Dynamic Inoperability Input-Output Model (DIIM)	8
Topological	34	Tree Analysis	8
Graph theory/model	28	Markov	7
Agent based	22	Game theory	6
Forecasting	15	Network theory	6
Hierarchical Methods (other)	15	Petri Nets	6
Uncertainty Analysis	15	Hierarchical Holographic Modeling	4
Bayesian	14	Quantitative Vulnerability Assessment	1
Fuzzy	13		

Significant changes between the master and interdependency sets based on the positioning of the M&S techniques in terms of their number of publications is summarized in Table 6 below.

Table 6. Comparison of position of M&S techniques based on number of publications between the master and interdependency sets.

M&S Technique	Position in Interdependency Set	Position in Master Set
Input-Output Modeling	4th	10th
Forecasting	10th	14th
Bayesian	13th	18th
DIIM	20th	28th
Clustering	15th	22nd
Game Theory	23rd	12th

While we do see some shifts between the two sets, the most prominent M&S techniques are relatively similar. The top five in the master set are Dynamic M&S, *Estimation, Statistical/numerical techniques,* *Classification/pattern identification, and GIS* which is tied for 5th place with *Graph theory/model* whereas the top five in the interdependency set are *Dynamic M&S, Estimation, GIS, Input-Output Modeling and Classification/pattern identification.* The only notable difference in the top five, as pointed out in Table 6, is the rise of *Input-Output Modeling* into the top 5 in the interdependency set. *Input-Output Modeling* is based on Wassily Leontief's economic input-output model and conceives of interconnected critical infrastructure systems as having inputs of failure due to disasters or acts of terrorism and outputs as the risk of inoperability due to the inputs.[42]

4.4.1.1 Interdependency M&S Emerging Trends

In order to identify emerging research trends in the modeling and simulation of interdependencies in CIPR, an R&D momentum analysis was conducted. Further explanation of the methodology behind the momentum indicator is included in Section 7.3, but as a reminder, this technique essentially plots the standard deviation of standardized measures of publication counts and velocity (the rate of publication increase) on two axes. Nodes which plot to the left of the Y-axis intersection have below-average velocity, and those which are found below the X-axis have relatively smaller publication counts. A third dimension is added by sizing nodes relative to the total number of underlying publications. Even a small node which plots to the right/lower side of the axes may be of interest, since emerging topics are typically small in numbers as they begin to attract research attention and increase in velocity. Figure 21 plots all 27 modeling and simulation techniques based on the records in the interdependency set.

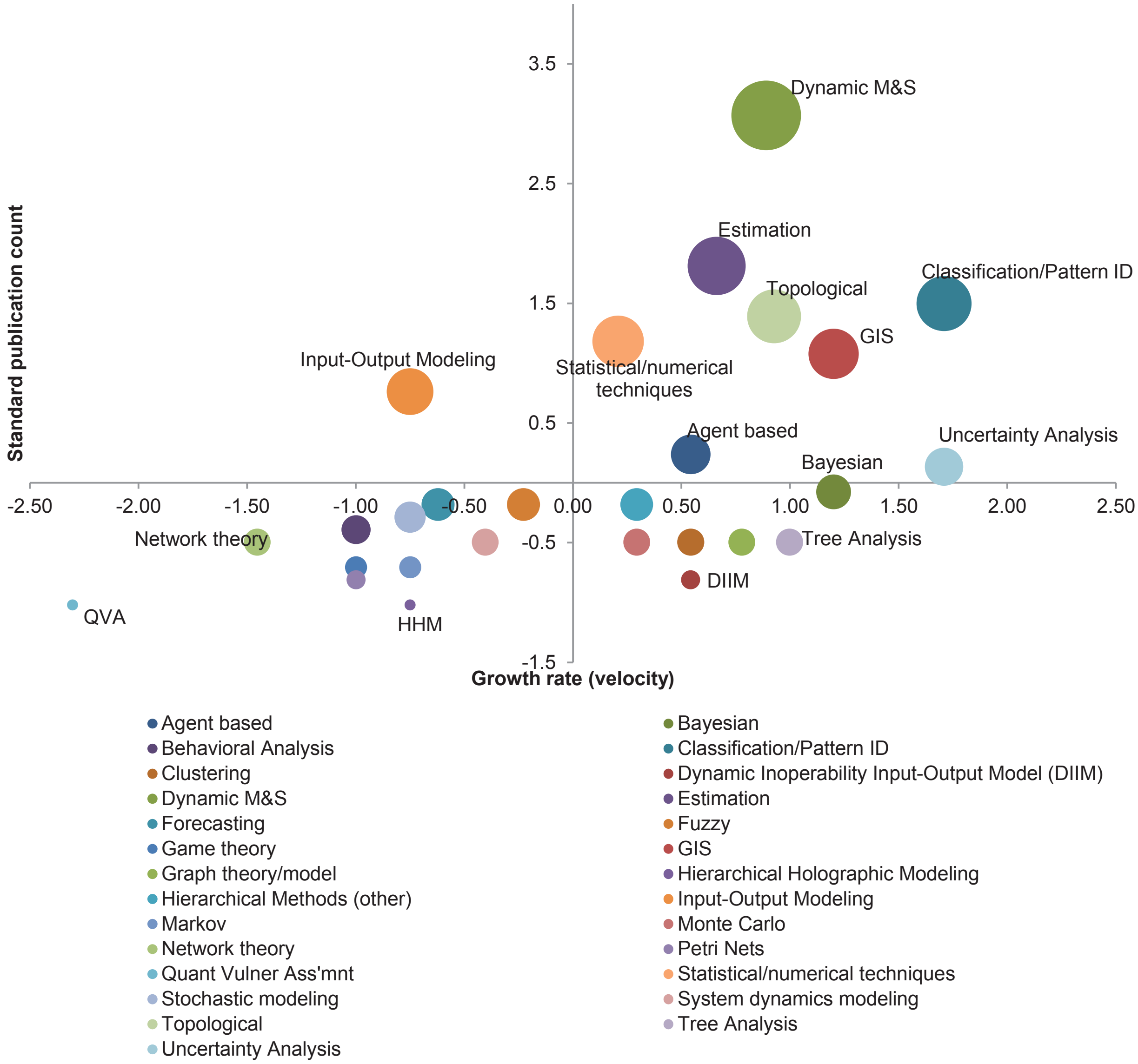

Figure 21. Interdependency Set, Modeling and Simulation R&D Momentum

As in the master set, the majority of the M&S fall below the x-axis. M&S that are already "hot" in the field with high number of records and a high rate of acceleration closely resemble the master set with *Dynamic M&S*, *Estimation*, *Statistical/numerical techniques, GIS,* and *uncertainty analysis* repeating in this quadrant. New additions to the top right quadrant include *Agent based* and *Topological* which were established trends in the master set. The only established trends in the interdependency subset appears to be input-output modeling which also rose in the M&S ranking in Tables 5 and 6 . In order to assess whether the remaining M&S are emerging topics in relation to CIPR, the number of publications for each node in the lower right quadrant is provided for the past 5 years[j].

[j] Insufficient data prevented us from presenting a figure for "new" or "disappearing" techniques in the interdependency set.

Figure 22 presents the M&S techniques that fall in the lower right quadrant, or the "emerging" techniques quadrant. Most notably we can see a significant jump in the use of *Bayesian* techniques and a doubling in *Tree analysis* (as was seen in the master set as well). Two examples of the use of *Bayesian* techniques from the interdependency dataset include Nechita, Muraru and Talmaciu who used a Bayesian approach to uncertainty to create a framework for the assessment of risk probability with a particular focus on information systems in critical infrastructure[10] and Di Giorgio and Liberati who presented a novel approach to CI interdependency analysis based on Dynamic Bayesian Network (DBN) formalism.[13] Tree analysis has been used to study the impact of an earthquake on the interdependent critical infrastructure (including power, water and *Transportation*) that are connected to nuclear power plants,[18] as well as in the creation of tools to support policy makers working on the resilience of interdependent CI that simulates the landscape of possible outcomes due to different policies.[43]

	Year				
Modeling and Simulation Technique	**2008**	**2009**	**2010**	**2011**	**2012**
Bayesian		2	1	1	6
Graph theory/model		1	1	2	2
Hierarchical Methods (other)	1	1	3	3	1
Monte Carlo		2		1	3
Dynamic Inoperability Input-Output Model		1			2
Tree Analysis			2		4
Clustering	1	1		2	2

Figure 22. Interdependency Set, Modeling and Simulation Techniques by Year, Nodes in Lower Right Quadrant – Emerging Techniques.

4.4.1.2 Interdependency M&S and Threat

Figure 23 identifies M&S techniques most frequently associated with each threat in the interdependency set.

	Threat													
Modeling and Simulation Technique	Disasters	Earthquake	Terrorism	Natural Disaster	Floods	Hurricane	Climate change	Blackout	CBRNE	Extreme weather	Denial of service Attack	Fire	Disease/ pan/ epidemic	Tsunami
Dynamic M&S	14	10	9	11	5	5		2	2	4	2	1		1
Estimation	3	10	4	4	4	2	8	3	2	2	1	1	1	1
GIS	9	5	6	3	7	3	1		2	2	1	5		
Input-Output Modeling	12	2	10	8	1	2		1	1		1			
Statistical/numerical techniques	9	6	2	2	4	1	3		4	2	1		3	1
Classification/Pattern ID	10	5	3	4	1	4	2	3	1	3				1
DIIM	7	1	2	5	1	1					1			
Graph theory/model	5	4	1	2	2						1	1	1	
Topological	5	3	2			3					1	2	1	
Forecasting	1	1	1	1	3	1	2			3	1			
Stochastic modeling	4	1	2	3	1			2						
Uncertainty Analysis	2	2	2	1	2	1	2		1					
Agent based	2	1	1	1				3	1		1	1	1	
Hierarchical Methods (other)	4	2	1	3				1						1
Monte Carlo	2	3	1		1			1	2					
Fuzzy	3	1	1		1		1					1		
Markov	2	1		1	2				1	1				
Behavioral Analysis	3	1	1						1					
Tree Analysis		2	1		1	1	1							
Petri Nets	1			1	2			1						
Bayesian	1				1		2							
Hierarchical Holographic Modeling			2	1										
System dynamics modeling	1	1				1								
Game theory			1								1			
Network theory								1						

Figure 23. Modeling and Simulation Technique by Threats, Interdependency set

Table 7 highlights the frequency with which each of the top 5 M&S techniques are used by various threats as well as the individual threat that uses each technique most often.

Table 7. Frequency of use of top five interdependencies M&S by various threats

M&S Technique	Frequency of use by threats	Threat that is the most frequent user of the technique
Dynamic M&S	Disasters (14), Natural disasters (11) Earthquakes (10), and Terrorism (9)	Disasters
Estimation	Earthquakes (10) and Climate change (8)	Climate change
GIS	Disasters (9), Floods (7), Terrorism (6), Earthquake (5) and Fire (5)	Fire
Input-output modeling	Disasters (12), Terrorism (10), and Natural disasters (8)	Terrorism
Statistical/numerical techniques	Disasters (9), Earthquakes (6), *CBRNE* (4) and Floods (4)	*CBRNE*, Disease/pan/epidemic

Interestingly, *Dynamic Input-Output Inoperability Model (DIIM)* is also fairly high up in the list, and is significantly higher than in was in the master set, with 50% of these records dating to 2013.[k] *Dynamic Input-Output Inoperability Model (DIIM),* which is an extension to the static Inoperability Input-Output Model (IIM) is based on Leontief's Input-Output model. *DIIM* is designed to analyze how a system of interdependent sectors can be adversely affected as a result of initial perturbations to other sectors through willful attacks or natural disasters.[44] The dynamic extension of IIM analyzes different temporal frames of recovery and characterizes the required sector adjustments for achieving new production levels.[45] DIIM is used most frequently in *Disasters* (7) and *Natural disasters* (5). These records discuss, among other topics, the use of *DIIM* along with the Bureau of Economic Analysis (BEA) and the Regional Input-Output Multiplier System (RIMS II) commodity-flow data of 59 sectors in Virginia to model a terrorist attack scenario[46] as well as in a denial of service attack on IT infrastructure to model highly affected economic sectors,[47] and as a method of modeling workforce disruptions in the aftermath of hurricanes.[48] Xu and his colleagues have also written two articles in 2013 describing a variety of uses of *DIIM*.[49,50] Unlike in the master set, *Game Theory* is rarely used in interdependency modeling showing up only once in *Terrorism* and once in *Denial of service attacks*.

4.4.1.3 Interdependency M&S and Critical Infrastructure

Similar to exploring the overlaps between M&S techniques and threats, Figure 24 presents a co-occurrence matrix of M&S techniques with the critical infrastructure presented in Figure 18. The most frequently used M&S for each CI is listed in Table 8.

[k] As mentioned previously, data from 2013 is not included in the R&D momentum analyses and thus may explain why DIIM does not show up as prominently above.

Table 8. Most frequently used M&S for each critical infrastructure

Critical Infrastructure	Modeling and Simulation Technique
Energy and Utilities	Dynamic M&S (27)
Transportation	Dynamic M&S (17)
ICT	Dynamic M&S (16), Topological (16)
Safety	Dynamic M&S (15)
Water	Estimation (13), GIS (13)
Health Care	Estimation (8)
Finance	Input-Output Modeling (9)
Buildings	Dynamic M&S (7)
Government	Dynamic M&S (5), GIS (5)
Military	Topological (5)
Cyber	Dynamic M&S (5)
Manufacturing	Dynamic M&S (7)
Coastal zone	GIS (5)
Public Infrastructure	Dynamic M&S (3), Estimation (3), Classification/Pattern ID (3)
Food	Dynamic M&S (4)

Table 8 shows, once again, that *Dynamic M&S* is the most frequently used modeling and simulation technique in the interdependency set, with a total of 65 records and 10 CI sectors favoring it. Six other techniques have over 30 records each including, *Estimation* (52), *GIS* (39), *Input-Output modeling* (38), *Classification/pattern identification* (36), *Statistical/numerical techniques* (35) and *Topological* techniques (34).

The majority of the techniques in Figure 24 are most frequently seen in use by the *Energy and Utilities* sector, however this is possibly due to the fact that this sector is quite a bit larger (in terms of number of records, 250) than the others. Similar to the master set, we see a predominant use of *Topological* M&S techniques in *Energy and Utilities* (23) as well as *ICT* (16), (*ICT* also used *Dynamic M&S* as frequently as *Topological* techniques). *GIS* is used most frequently by *Energy and Utilities* (16) followed by *Safety* and *Water* (13 each). *Input-Output modeling* is seen most frequently in *Energy and Utilities* as well as *Finance* (9 each). *Hierarchical methods* are used most frequently by *ICT* (9). *Clustering* is used most often in *ICT* (4), *Transportation* (4) and *Water* (4). Similarly *System Dynamics Modeling* is most often used in *Transportation* (4), *Water* (4) and *Energy and Utilities* (4). *Network theory* is most frequently used in *ICT* (4) and *Energy and Utilities* (4). We only see *Quantitative Vulnerability Assessment* in *Energy and Utilities* (1).

Modeling and Simulation Technique	Critical Infrastructure														
	Energy and Utilities	Transportation	ICT	Safety	Water	Health Care	Finance	Buildings	Government	Military	Cyber	Manufacturing	Coastal zone	Public infrastructure	Food
Dynamic M&S	27	17	16	15	8	6	6	7	5	4	5	7	4	3	4
Estimation	17	12	10	11	13	8	2	4	1	1	1	5	3	3	3
GIS	16	11	6	13	13	4	1	4	5	2		1	5	2	
Classification/Pattern ID	15	16	7	3	7	7	4	6	2	2	2	3	2	3	
Topological	23	6	16	3	5	1	3			5	2		1		
Agent based	12	8	10	2	3	2	5	2	2	2	4	4			2
Graph theory/model	14	10	10	5	5	2	1	1	2	4	2	1	1		
Statistical/numerical techniques	11	4	9	12	5	5	3	1	2	1		1	1	1	
Input-Output Modeling	9	6	6	2		3	9	1	3		4				1
Hierarchical Methods (other)	8	3	9	3	1	2	2	3	1	2	2	2		1	
Fuzzy	5	4	1	3	3	3	1	3		3	1	1			
System dynamics modeling	4	4	3	3	4	3	1	2	3					1	
Forecasting	5	3	5	3	1				3	2	2	1	2		
Clustering	2	4	4	1	4	1	2	1	1		1	1	1	2	1
Bayesian	7	5	2	4	2	1				2			1		1
Stochastic modeling	7	3	1	2	2	1	1	1	2	1		2			
Uncertainty Analysis	7	1	2	2	4	1		1			1	1			2
Tree Analysis	4	3	1	3	2	1	1			2	1	1	1		
Behavioral Analysis	4	3	2	2	2		1		1			1		1	1
Monte Carlo	6	3		3	3					1					
Game theory	4	2	2		2		1			2	1		1		
Network theory	4	2	4		1				2		2				
Hierarchical Holographic Modeling	2	2	2				3			1	3				
Petri Nets	4	2		1	3				1						
Markov	3	1		1	2										
DIIM	1		1			1	2		1						
Quant Vulner Assessment	1														

Figure 24. Modeling and Simulation by CI, Interdependency set

4.4.1.4 Interdependency M&S by Government Level

Figure 25 displays the co-occurrence of each type of government body with the 27 M&S techniques. Because the interdependency set was created by extracting all records from the master set that included the terms “regional” and “local” (in addition to interdependency and it’s synonyms), it is unsurprising to see higher number of records for most M&S techniques in the regional/local group. The top five techniques used by the *Regional/local* group include *Dynamic M&S* (27), *Estimation* (24), *GIS* (22), *Statistical/numerical techniques* (16) and *Input-Output modeling* (15). At the *National* level, *Dynamic M&S* (17) is followed by *GIS* (11) and then *Agent based* techniques, *Input-Output modeling*, and *Classification/pattern identification* with 8 records each. *Government* uses *Dynamic M&S* most frequently (5) followed equally by *GIS, Input-Output Modeling Forecasting,* and *System dynamics modeling* (3 each). The *Department of Homeland Security* and the *Military/DoD* show up very little in this graph with only one record in a few M&S techniques except for *Input-Output modeling* which has 2 records in the *Department of Homeland Security* group. This is somewhat surprising since we know that the DHS is working on CIPR interdependency but this may be due to their work in this specific area not being captured in the databases that were searched or perhaps to their work being commissioned by associated bodies such as Sandia National Labs or Idaho National Labs and therefore not being grouped as a DHS record.

Modeling and Simulation Technique	Regional/local	National	Government	Dept Homeland Security	Military/DoD
Dynamic M&S	27	17	5	1	1
GIS	22	11	3	1	1
Estimation	24	5	2		
Input-Output Modeling	15	8	3	2	
Classification/Pattern ID	14	8	1		1
Statistical/numerical techniques	16	3	1		
Forecasting	11	4	3		1
Agent based	4	8	2	1	1
Hierarchical Methods (other)	5	3	1		1
Graph theory/model	4	3	2		
Stochastic modeling	2	3	2		1
Behavioral Analysis	3	2	1	1	
Clustering	4	2	1		
System dynamics modeling	1	3	3		
Uncertainty Analysis	6	1			
Dynamic Inoperability Input-Output Model	3	2	1		
Topological	4	1			1
Bayesian	4	1			
Fuzzy	3	1			1
Hierarchical Holographic Modeling		2	1		
Tree Analysis	1	2			
Markov	2				
Monte Carlo	2				
Network theory		2			
Game theory		1			
Petri Nets			1		

Figure 25. Modeling and Simulation Technique Usage by Government Levels, Interdependency set

4.4.2 Interdependency/Regional Tools

In addition to the groups presented in the master set, three additional groups were made[l] to capture *Interdependency tools* (with a total of 135 *records*[m]), *Regional tools* (with a total of 42 records) and *Government/business continuity tools* (with a total of 14 records*)*. Furthermore, each previously identified tool was searched for in the master set and a group was created with 76 individual tools. It should be noted that additional tools exist but are not searchable due to the lack of specificity in the searched database (i.e. an article made reference to a "suite of tools" but did not name them. In these cases, some other useful reference to the tool was searched). A co-occurrence matrix of the M&S techniques and these three new groups was created and is presented in Figure 26.

Modeling and Simulation Technique	Interdependency Tools 135	Regional Tools 42	Gov't/Business Continuity Tools 14
Dynamic M&S	19	13	2
Agent based	10	1	1
Estimation	10	5	1
Input-Output Modeling	10	9	
Statistical/numerical techniques	10	4	
GIS	9	5	
Dynamic Inoperability Input-Output Model (DIIM)	8	8	
Petri Nets	7		
Forecasting	6	5	
Graph theory/model	6		
Stochastic modeling	6	1	1
Bayesian	5		1
Monte Carlo	5	1	
Uncertainty Analysis	5	3	1
Classification/Pattern ID	4	2	
Hierarchical Methods (other)	4	3	
Topological	4	1	
Fuzzy	3	2	
Network theory	3		
Clustering	2	1	
Behavioral Analysis	1		
Game theory	1	1	
Hierarchical Holographic Modeling	1		
Markov	1		
Tree Analysis	1		
System dynamics modeling		1	

Figure 26. Modeling and Simulation by Interdependency / Regional / Gov't Continuity Tools

Interdependency tools tend to use *Dynamic M&S* (19) nearly twice as often as the next most frequent modeling techniques: *Agent based* techniques (10), *Estimation* (10), *Input-Output modeling* (10) and *Statistical/numerical techniques* (10). *DIIM* (8) and *Petri nets* (7) are relatively high on the list as well.

Table 9 lists some of the tools found in these M&S Techniques.

[l] These three groups were built in the master set based on a field that combines abstracts (in full) and all the keyword fields that was used to create the groups presented earlier in the report.

[m] The total number of records is not a count of the number of tools in the group but the number of records (or publications) that discuss one of the tools. For instance, there are 13 records that discuss RAMCAP.

Table 9. Top M&S Techniques along with Selected Interdependency Tools

M&S Technique	Selected Tools
Dynamic M&S	N-ABLE, Rapid Prototype, CI Risk Model, and CIPDSS
Agent –based Modeling	N-ABLE, IRRIIS, CRIPS, MIT and OMNet
Estimation	HAZUS-MH, CI Risk Model, N-ABLE and IRRIIS
Input Output Modeling	RIPS, ISA and REAcct
Statistical/numerical techniques	Fragility Curves, Muir Web, and PipelineNET
DIIM	DIIM
Petri Nets	Fragility Curves, GeoPN, Resilience Assessment Framework, Discrete Event Simulation

The *Regional tools* group, on the other hand, uses *Dynamic M&S* (13) most frequently followed by *Input Output Modeling* (9), *DIIM* (8), *GIS* (5), *Forecasting* (5), *Estimation* (5), *Statistical/numerical techniques* (4), and *Agent based* techniques (1). Specific *GIS* tools include Rapid Prototype, Regression Models, GeoPN, GONE, OMEGA, SWMPT while specific *Forecasting* tools include Rapid Prototype, SERSCIS ICT, MIMESIS and Secure Mediation Gateway to list a few.

The *Government and business continuity tools* group use *Dynamic M&S* (2) and the following techniques one time each; *Estimation, Agent based modeling, Bayesian* techniques*, Stochastic Modeling* and *Uncertainty Analysis*. The two tools that are specifically mentioned by name in this group include the EASI model and the OTB SAF simulation tool.

Other tools that are specifically named and grouped in the *Government and business continuity tools* group but do not show up in this co-occurrence map (because they do not specify a technique) include:

- Flowroute,
- Resilience Evaluation System,
- Infrastructure Survey Tool,
- Community Preparedness and Response (CPR) model for local governments,
- CERT Resiliency Engineering Framework,
- RAMCAP-PLUS,
- EASI model,
- OTB SAF simulation tool,
- Infrastructure Analysis System (IAS), and
- OMEGA.

A second co-occurrence matrix of the critical infrastructure and these three groups of tools is presented in Figure 27.

Critical Infrastructure	Interdependency Tools 135	Regional Tools 42	Gov't/Business Continuity Tools 14
Energy and Utilities	57	13	4
ICT	49	7	1
Transportation	31	10	3
Safety	30	12	2
Water	18	6	4
Health Care	16	8	2
Finance	15	4	3
Cyber	13	2	
Buildings	12	3	1
Manufacturing	11	7	2
Government	8	8	3
Food	5		
Coastal zone	4	3	
Public infrastructure	4	2	
Military (CI)	3	1	1

Figure 27. Critical Infrastructure by Interdependency / Regional / Gov't Continuity Tools

Unsurprisingly, we see that the five largest CI sectors in the interdependency set are the ones that are most frequently using interdependency tools. Table 10 lists some of the tools in the top sectors along with examples of scenarios in which they have been used.

Table 10. Top 5 Sectors, Tools Used, Scenarios of Use

Sector	Tools	Scenarios of Use
Energy and Utilities	MIT, CIMS, CIPDSS-PST, RESC-MONITOR, Flow Assurance by Management of Uncertainties and Simulation (FAMUS) and MOCA-RP software, PSS®SINCAL, M-CI2	• In Canada, the M-CI2 has been used to model cyber interdependencies of critical infrastructure in the event of power outages[51]
ICT	MIT, CIMS, RESCI-MONITOR, M-CI2, OMNET++, N-SMART	• OMNET++ has been used to simulate wireless sensor networks[52] • Host-Based System Security software agents by JTF-GNO has been used to assess cyber damage to command and control information technologies,[53] • (N-SMART) has been used to assess impact of disasters (e.g. hurricanes) on telecommunication networks amongst others[54]
Transportation	N-ABLE, CIMS, CIPDSS and RESCI-MONITOR	• N-ABLE has been used to simulate the economic impact of infrastructure interdependencies due to shipping port closures in the *Transportation* sector[55]
Safety	CAX, SNA-GIS, N-SMART tool, CRIPS, CIMS and PSS®SINCAL	• CAX (computer assisted exercises) has been used to simulate CI interdependencies in the area of civil protection • SNA-GIS (a social network analysis – geographic information system tool) has been used to analyze CI hazards and threats to security[56]
Water	ADWICE, PSS®SINCAL	• ADWICE for real-time anomaly detection in water management systems[57]

One tool that crosses most of the top five CI in the project is the MICIE platform. MICIE is an on-line risk assessment tool that can be used in scenarios with interdependent CI including power distribution networks, power plants, refineries, water distribution networks, transportation systems and telecommunication networks.[58,59]

Finance is in the 7th place in the Interdependency tools, using these tools more than would be expected given that they are the 10th (out of 15) largest CI in the interdependency set. The *Military* also appear to be using these tools less than expected, given that they are the 8th largest CI in the interdependency set but place 15th in their usage of these tools.

In terms of the *Regional tools*, *Energy and Utilities* tops the list with 13 records. This is closely followed by *Safety* (12), *Transportation* (10), *Government* (8) and *Health Care* (8) – both of which are below the top 5 in the overall interdependency CI sector rankings. The *Government* CI sector used the following tools:

- Complex Event Modeling,
- Simulation and Analysis (CEMSA),

- the Homeland Security Regional Cooperation Areas (HSRCAs) conceptual model,
- Operational Multiscale Environment Model with Grid Adaptivity (OMEGA) to model the release of anthrax in the national capital region,[60]
- RAMCAP, and
- HAZUS-MH to name a few.

The *Health Care* sector used PipelineNET to model safe drinking water[61], RAM-W, OMEGA and RAMCAP repeatedly. The *Military* and *Food* are at the bottom of the list of users of regional tools.

In terms of *Government/business continuity tools*, *Energy and Utilities* and *Water* have the most records (4) each followed by *Government*, *Transportation* and *Finance* with (3) each. Flow route, Community Preparedness and Response (CPR), Infrastructure Analysis System (IAS) and RAMCAP Plus are discussed in the *Energy and Utilities* and *Water* sectors. RAMCAP Plus is also discussed in *Safety* and *Manufacturing*. The CPR model is discussed in the *Transportation*, *Government* and *Finance* sectors and the CERT Resiliency Engineering Framework and IAS are also discussed in *Government* and *Finance*.

Six Canadian affiliations are associated with various interdependency tools or techniques including:
- University of British Columbia, Vancouver, BC – development of interdependency modeling tools that include physical and social interdependencies to aid decision support.[62]
- York University, Toronto, ON – M-CI2 project which models interdependencies using social network and reliability modelling techniques; simulates infrastructures using techniques from the complex adaptive systems field[51]; and developed the GeoPetri Net system, which can be used to simulate the complex geographical relationships among places and nodes. A case study involving an education layer with 15 nodes (schools) and a transportation layer with 25 node lines (streets) in a geographical information system is presented.[63]
- University of Toronto, ON – the use of social network analysis to study human interactions and to analyze interdependency characteristics of critical infrastructure networks.[64]
- Concordia University, Montreal, QC – an integrated modeling method for simulating the vulnerability of a critical infrastructure for a hazard and the subsequent interdependencies among the interconnected infrastructures.[65]
- University of New Brunswick, Fredericton, NB - the integration of context-aware modeling as a tool for controlling the clustering mechanism through which the eNetwork self-organizes its services to tune its resilience according to the dynamics of an occurring situation.[66]
- Ecole Polytechnique de Montreal, QC - a concrete set of tools (consequence curves and flexible cartographic representations) enabling the visualization of cascading effects and management of physical interdependencies among the CI.[67]

4.5 Lessons Learned in CI Modeling and Simulation

There is a general lack of specific best practices or lessons learned in the reviewed literature. This may mean that the field of modeling and simulating critical infrastructures, and in particular CI interdependencies, has not yet matured. In general, articles that did provide best practices, lessons learned, or recommendations were either presented at a higher level focused on managing risks or disaster response or were more specific to the tool and specific case study being presented that they were not easily generalized to M&S of CI interdependencies. Two areas that did seem to have more general recommendations than others was the protection of CI from cyber-attacks and climate change impacts, but again these were not specific to M&S.

Ouyang[2] identifies four key areas in which CI interdependency M&S research challenges lie. These areas are reiterated, to various extents, by other authors as well.[3,40,68-70]

- Data access and collection
  - Difficult to access data or lack of precise data is a key problem in the field.
- Comprehensive modeling and analysis
  - Due to interdependencies, all CI, including those that receive less attention such as finance and commercial and government facilities should be included in CI modeling to improve disaster mitigation and recovery.
  - An open modeling framework to capture short and long term changes and evolution in CIs is desired.
- Integration and co-simulation
  - The variety of tools and techniques for M&S capture different aspects of interdependencies with varying levels of error and uncertainty and potentially conflicting results.
  - Integration of these techniques, with clear roles, into a uniform framework is needed.
- Validation and applications
  - Validating new models outputs to historical data (the norm) is not always appropriate as CI and their environments are constantly changing.
  - A comprehensive and standard set of metrics, guidelines and standards are needed to demonstrate the applicability of different modeling and simulation approaches and how they can inform different types of decisions.

In 2011, the U.S. Department of Homeland Security and the National Institute of Standards and Technology produced a series of recommendations on M&S CI systems (not specific to interdependencies) for homeland security applications.[70] They identified several issues that remained to be addressed in the field, including but not limited to:

- Identification of appropriate models, simulations, tools and databases to address critical infrastructure and key resources (CIKR) analysis needs, that can be shared by sector specific agencies with the user community;
- Identification of technical gaps for models, simulations, tools and databases;
- Development of system requirement specifications for CIKR models, simulations, tools and databases;
- Development of systems dynamics models for addressing strategic issues for different CIKR sectors and systems;
- Development of mechanisms to enable access to and usage of CIKR M&S applications by Sector Specific Agencies, CIKR partners, and operational personnel;
- Development of simulation application architectures to enable module integration and standard data interfaces to import data from external databases;
- Use of a system of systems engineering approach to the development of applications;
- Development of M&S applications as open systems;
- Use of object-oriented models in CIKR M&S;
- Integration of CIKR models and simulations;
- Establishment of security and protection mechanisms for sensitive data;

- Ownership and usage of publicly vs. privately developed models, simulations, tools, and databases; and
- Return on investment to stakeholders and sponsors for research projects.

Both of these overviews of recommendations highlight the lack of maturity in the field and the need for continued development.

5 CONCLUSIONS

To help support CSS in their long term goal of developing an integrated national and regional Critical Infrastructure (CI) Dependency model for CI risk analysis and risk mitigation in support of the CI strategy, NRC Knowledge Management has performed an exploratory study of existing scientific, industrial and government (domestic/international) literature on critical infrastructure protection and resilience (CIPR) and has reported on modeling and simulation tools and trends.

The number of different tools that can be used, are being designed or researched to model and simulate CIPR is quite high. There were over 600 records that mention tools or software in the master set of 2151. While these tools were not individually listed, 113 tools used for interdependency modeling or regional/local modeling or government/business continuity were examined. The majority of these tools (82) are grouped as *Interdependency* modeling, with 18 falling into the *Regional* group and 13 in the *Government/business continuity* group.

The results of this study show that there are not many differences in modeling and simulation techniques that are used for general CIPR or CIPR interdependencies. *Dynamic Modeling and Simulation* is the most frequently used technique for CIPR both in the tools that were examined and from a theoretical standpoint in the data sets. *Dynamic M&S* can be found in N-ABLE, Rapid Prototype, CI Risk Model, and CIPDSS to name just a few specific tools. *Estimation, Statistical/Numerical techniques, Classification/Pattern Identification, GIS, Graph Theory/Model,* and *Input-Output modeling* were among the top techniques as well.

In terms of CIPR M&S in general, the use of *Bayesian* techniques and *Fuzzy* techniques can be seen in the “brand new” quadrant of the R&D momentum analysis. In terms of emerging techniques, *Tree Analysis* as well as *Behavioral Analysis* and *Monte Carlo* techniques are gaining popularity for general CIPR M&S. In terms of emerging techniques, *Bayesian, Tree Analysis* and *Monte Carlo* are proving to be useful for interdependency M&S.

CIPR modeling and simulation as well as interdependency tools are most frequently used in the *Energy and Utilities* sector followed by *ICT*, *Transportation* and *Safety* both in terms of individual and interdependency modeling. These tools are most frequently applied to model or simulate CIPR in response to *Disasters*, *Terrorism, Earthquakes* or *Natural Disasters*.

The United States followed by Italy and Canada are the predominate nations working on CIPR modeling and simulation as per our dataset. Within the United States, the National Laboratories, including Sandia and Idaho have extensive CIPR programs and are producing interesting tools and technologies. In Italy, the main author affiliations are also governmental including ISPRA and ENEA, both of which are working on Pan-European CIPR projects. Within Canada, the University of British Columbia, York University and Western University figure prominently, all of which are involved in either the Joint Infrastructure

Interdependencies Research Program or the Disaster Response Network Enabled Platform. A few additional affiliations rose to the top of the list in the interdependency set including Polytechnic University of Milan (Italy), Huazhong University of Science and Technology (China), University Campus Bio-Medico of Rome, Rice University (U.S.), the Italian National Research Council (CNR), TNO Defense (Netherlands) and Gjøvik University College in Norway.

Finally, the similarities between the two data sets (CI M&S and CI interdependency M&S) are quite notable. It is possible that the subfield of CIPR interdependency modeling and simulation is still depending on tools and techniques used in general CIPR modeling because it has not yet developed enough of its own tools and techniques. The only exception is the advancement of *Input-Output Modeling* to include the Dynamic component in the creation of *Dynamic Inoperability Input-Output Modeling* to specifically model interdependencies. Despite this modest advancement, Ouyang[2] argues that there is still a need for a new concept that can "integrate different approaches into a single framework and co-simulation platform to address different aspects of interdependent" critical infrastructure. This alternative view is supported by the general lack of specific best practices or lessons learned in the literature that was reviewed, i.e. the field of modeling and simulating critical infrastructures, and in particular CI interdependencies, may not yet have matured enough to have best practices. In general, articles that did provide best practices, lessons learned, or recommendations were either presented at a higher level focusing on managing risks or disaster response or were more specific to the tool being presented and not easily generalized to M&S of CI interdependencies. Alternatively it may be that the tools and techniques that are used in general CIPR modeling are sufficiently applicable to interdependency modeling. More time and testing of these techniques would be required to determine the true cause of the overlap. Revisiting the numerous projects and programs that were presented in the key players section would allow one to keep a finger on the pulse of developments in this area.

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7 METHODOLOGY

7.1 Search Strategy

A literature search was conducted in the Scopus, IE Compendex, Inspec and National Technical Information Service (NTIS) databases. The basic search strategy used to retrieve records was based on keywords shown in Table 11 below. Terms or phrases in columns A and B were combined using Boolean and proximity operators (AND, OR, NEAR) to cover all aspects of the problem. The search targeted substantive fields such as title, keywords (controlled and uncontrolled vocabularies) and abstracts. The time period was limited to records 2003 to the present.

Table 11. Search Terms

A: Critical infrastructure	B: Protection /resilience	C: Modeling and simulation	D: Risk/threats	E: Interdependency
• Critical infrastructure • Critical assets • Public infrastructure	• Protection • Resilien*	• Model* • Simulation* • Simulate • Tool • Software • Assess	• risk • threat • vulnerability* • disaster* • Emergenc* • Earthquake* • Tsunami* • All hazard* or multi hazard* or hazard* • (extreme or unforeseen) event* • Flood* or drought or fire* or wildfire* • Terroris* or extremis* • Epidemic* or pandemic* or health NEAR emergenc* • CBRN* or ((chemical or biolog* or radioactive or nuclear) NEAR warfare or weapon* or attack*)) • (Industrial or *Transportation* or chemical) NEAR (accident* or spill* or leak*) • cyber attack or cyberattack • cyber warfare	• Interdependen* • Regional dependenc* • regional interdependenc*

7.2 Analytic Tools

All references were downloaded into VantagePoint software for analysis. VantagePoint enables the creation of various groupings, statistical analyses, matrices, graphs, and cross-correlations to analyze the data and profile the activities of the major players. Once in VantagePoint, duplicate records in the data were removed and the records were prepared for analysis.

Keywords, identifiers (usually author-supplied keywords), descriptors, subject headings and terms from titles were merged together to facilitate subject analysis. These terms were then cleaned to harmonize variant spellings, acronyms and similar meanings. They were then organized into subject groups, which were defined based on the top terms and readings from references included in the dataset. Groups created during the analysis are provided as an attachment to this record, file name: KM-NRC 18526-122 Subject Groups. The four Thematic Groups are provided in section 7.2.1, Table 12.

Different analytical tools were used to generate graphs based on statistical operations performed in VantagePoint. TouchGraph software was used for cluster analysis and visualization of the subject groups while Tableau software was used to generate bubble graphs and some tables.

7.2.1 Thematic Groups

Table 12. Thematic Group

Thematic Group	Scope	Subject Groups	
Modeling and Simulation Techniques	The modeling and simulation techniques used in CIPR	Dynamic M&S Estimation Statistical/numerical techniques Classification/Pattern ID GIS Graph theory/model Topological Agent based Input-Output Modeling Hierarchical Methods (other) Game theory Uncertainty Analysis Forecasting Stochastic modeling	Fuzzy Behavioral Analysis Bayesian Monte Carlo System dynamics modeling Tree Analysis Clustering Petri Nets Markov Network theory Dynamic Inoperability Input-Output Model (DIIM) Hierarchical Holographic Modeling Quantitative Vulnerability Assessment
Critical Infrastructure	Physical structures or systems impacted by disasters. 10 are based on the Canadian CI sectors. Additional ones are added due to their prevalence in the dataset	Energy and Utilities ICT Safety Transportation Cyber Government Water Health Care	Buildings Military Finance Manufacturing Public Infrastructure Coastal Zone Food
Threats	Threats or accidents which may lead to emergencies or to	Terrorism Disaster Earthquake	Climate change Extreme weather Disease/pan/epidemic

Thematic Group	Scope	Subject Groups	
	disasters	*CBRNE* Natural Disaster Flood Fire Hurricane	Blackout Denial of service attack Tsunami Drought
Government Levels	Various levels of government or military that figure prominently in the dataset	Regional/Local National Government Department of Homeland Security	Military/DoD International

7.3 R&D Momentum

To ascertain the normalized growth rates and compare values according to their standard deviation for each of the subject groups in the thematic groups, we plotted publication numbers and the angle (slope) of their increase or decline over time over time (2008-2012), using linear regression. Average slope degrees and standard deviation were then calculated and standardized, to produce Z-scores, a measure of the relative rate of publishing increase (velocity).

Standardized publication counts were also produced for each of the subject groups analyzed. Plotted on 2-dimensional intersecting axes, the z-scores (velocity) and standardized publication counts (mass) provide an expression of the relative momentum of topics within each group.

This indicator is designed to identify rapidly rising subjects with relatively few publications. The challenge of identifying such subjects lies with the publication volume as a confounding factor, for their rapid growth and evolution is dwarfed by the high volume of established subjects. Specifically, the notion of “emergence” consists not only of a sharply rising trend line but also of a small footprint (low publication numbers) in the domain of interest. A *relatively* small footprint is the reason emerging subjects are often overlooked until their disruptive impacts become obvious.

The four-quadrant visualization provides a structured view of the relative position of these subjects within the group. The indicator can also be applied to identify differences between topics with small publication numbers but relatively greater velocity.

A third dimension is added by relating the size of each node to its actual publication count.

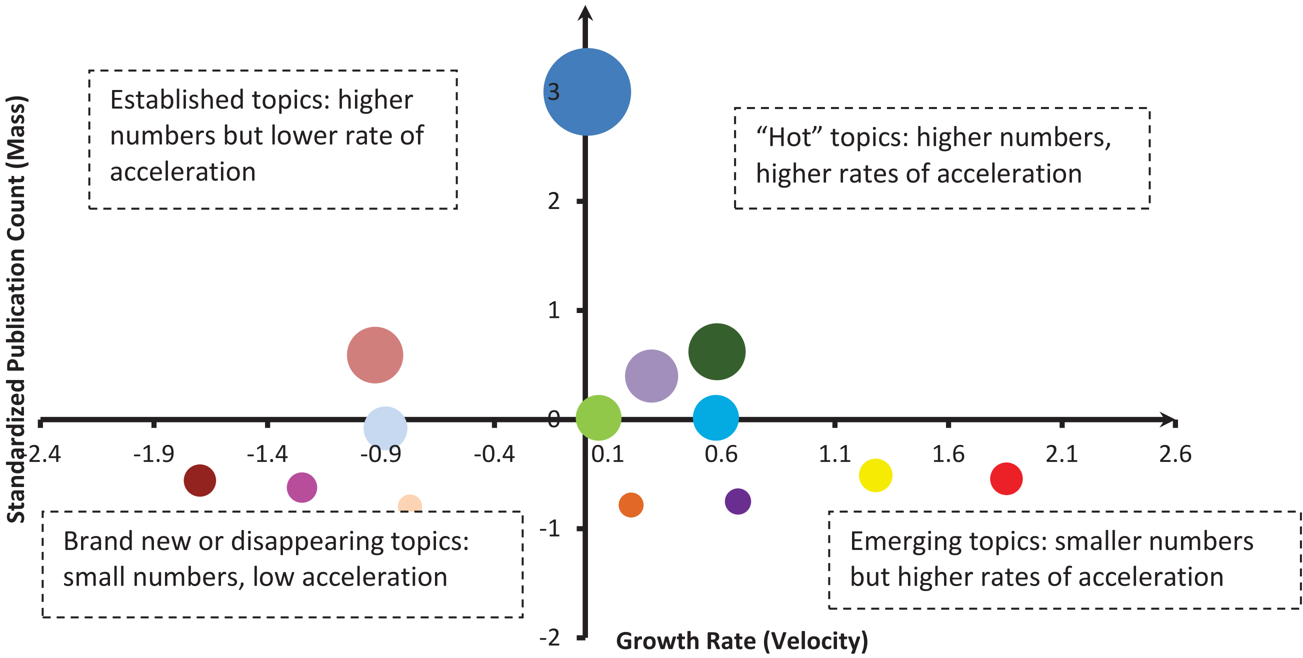

Figure 28. 4 Quadrants Momentum Indicator

One possible limitation of the methodology may be absent or incomplete publication values for certain years in a time series, so the analysis provided by z-scores should also be accompanied by a review of actual values over time wherever possible.

7.4 Sources Consulted

Licensed databases:

- Scopus
- EI Compendex
- Inspec
- National Technical Information Service (NTIS)